REPORT DOCUMENTATION PAGE

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	Technical Papers	

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12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

20030116 042

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
					Leilani Richardson
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
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Standard Form 298 (Rev. 8-98)
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MEMORANDUM FOR PR (In-House Publication)

FROM: PROI (TI) (STINFO) 19 Jun 2000

SUBJECT: Authorization for Release of Technical Information, Control Number: **AFRL-PR-ED-TP-2000-135**
Mead, F., "Beamed Energy (Laser) Propulsion"

AIAA Short Course **(Statement A)**
(Huntsville, AL, 21-22 Jul 2000) **(Submission Deadline: 9 Jun 2000)**

1. This request has been reviewed by the Foreign Disclosure Office for: a.) appropriateness of distribution statement, b.) military/national critical technology, c.) export controls or distribution restrictions, d.) appropriateness for release to a foreign nation, and e.) technical sensitivity and/or economic sensitivity.
Comments:____

Signature ________________________ Date ____________

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Comments:____

APPROVED/APPROVED AS AMENDED/DISAPPROVED

____

LESLIE. S. PERKINS, Ph.D (Date)
Staff Scientist
Propulsion Directorate

BEAMED ENERGY (LASER) PROPULSION
(A Perspective)

by

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Outline

- Preliminaries
- Historical Overview
  - The Early Years 1970-1990
- Concepts From The Early Years
  - Project Outgrowth
  - Paraboloid
  - Absorption Chamber
  - Heat Exchanger
- Developments In The 90's
  - Domenstic
    - NASA
    - Air Force (Lightcraft)
  - Foreign
- References

What is Laser Propulsion?

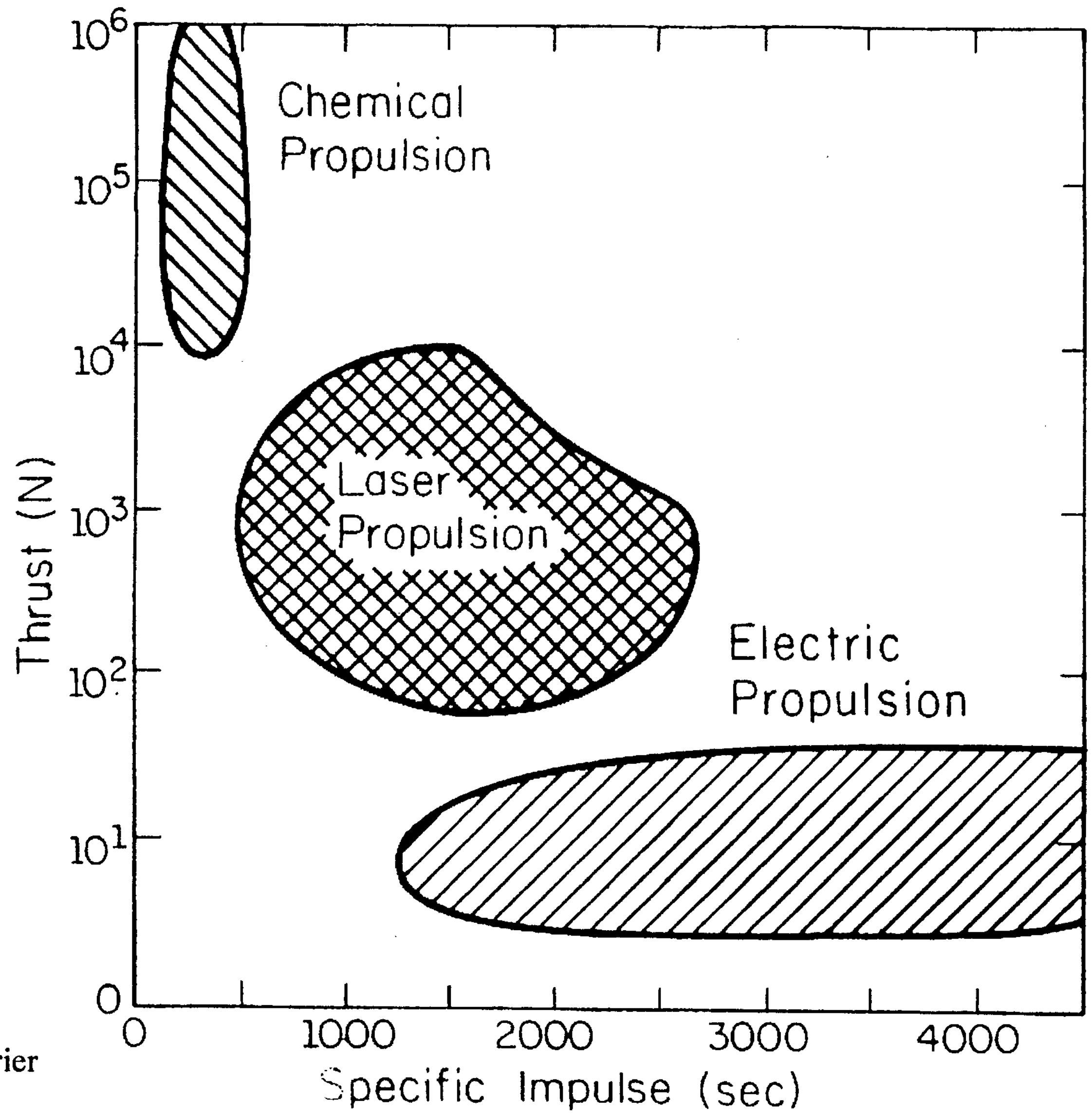
- Propulsion System Using (typically) External Laser Power Source (ground and/or space based)
  - Heats Propelland to Very High Temperatures
  - Provides Energy Source For Electrical Power Generation
  - Provides Direct Photon Force

"Laser propulsion is an idea that may produce a revolution in space technology."
JASON Laser Propulsion Study, Summer 77

Background

- Why Laser Propulsion
  - Decoupled Energy Source
  - High Specific Impulse (Isp) Potential
  - High Thrust Relative to Electric Concepts
  - Avoids the Radiation and Mass Penalties Inherent With Nuclear Propulsion
  - Technical Problems are not Fundamental
  - Econonomic Justification Concluded in Separate Studies by AF, NASA, & DARPA
- Mission Potential
  - Low Cost Access to Space
  - Orbit Raising
  - Kinetic Kill Vehicles (KKV)
- Problems
  - Lacks Complete Demonstration After 31 Years From Conception
  - Reduced Funding for Demonstration
  - Low Interest

Laser Propulsion Performance Relationships*



*U. Of Illinois report by Dr. Krier
Under AFOSR Contract

Propulsion Relations

<u>Rocket</u>:

F = Thrust
_ = Weight Flowrate
g = Gravitational Acceleration

- I_{sp} = F/_ ← Specific Impulse (s)
- P = _gFI_{sp} ← Exhaust Power (J)

why are these out in the middle?

<u>Pulse Jet</u>:

I = Impulse Bit (N-s/pulse)
E = Total Energy in a Laser Pulse (MJ/pulse)
t = Pulse Length or Width (s)
f = Pulse Frequency(s^{-1})

- η (CC or C_m) = I/E — Coupling Efficiency (N-s/MJ)
- F = η(E/t) = I/t ← Thrust per Pulse (N)
- $F_{av} = f(Ft) = f(\eta E) = fI$ ← Average Integrated Thrust
- $F_{lbs} = F_N/4.45$ ← Conversion to Pounds of ? Thrust

Brief History

Beamed Energy Rockets

- Microwaves – Willinski (1959)
- Lasers – Light Sails – Forward (1962)
  - Rockets – Geisler (1969), Kantrowitz (1972)

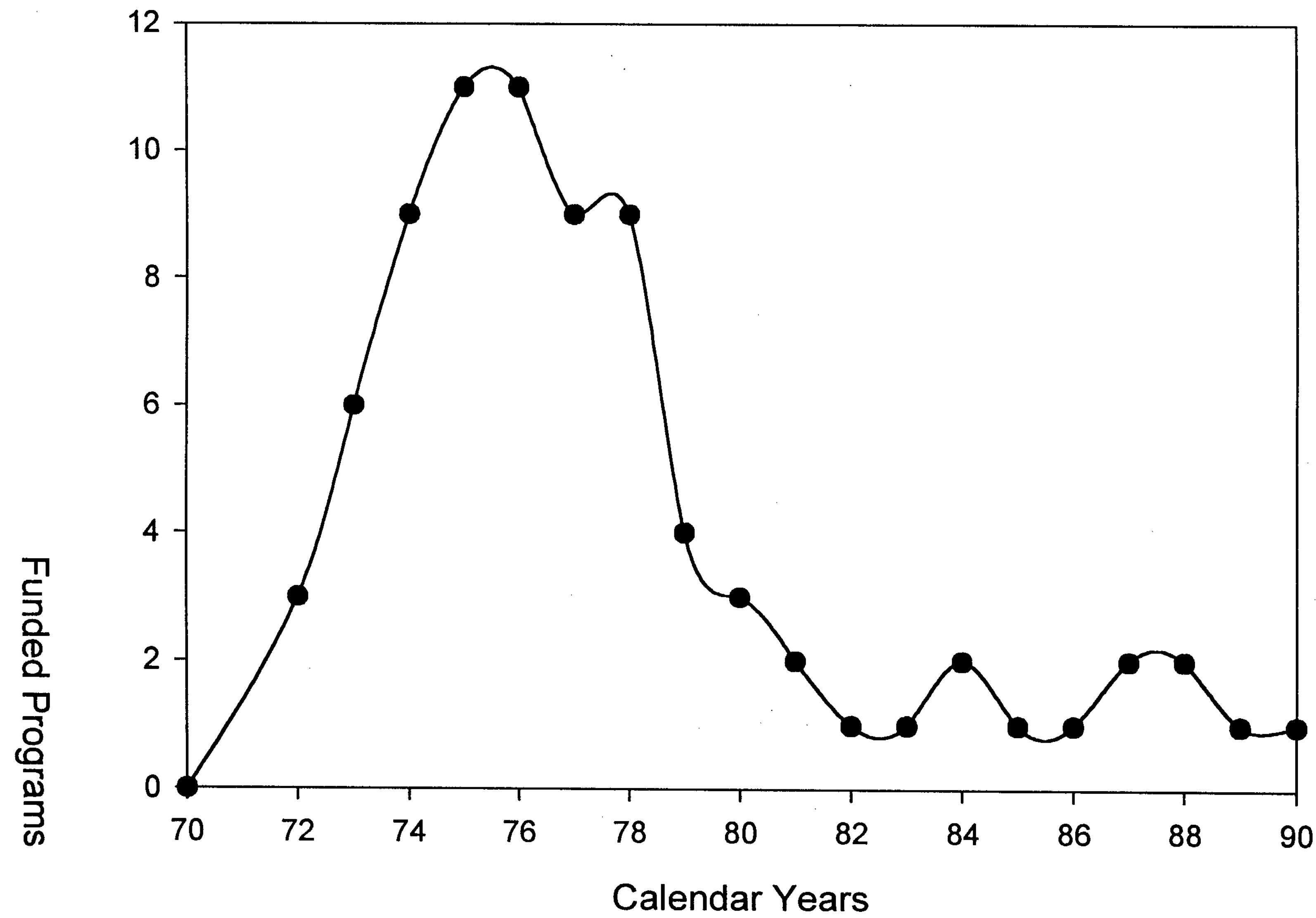
Propulsion Activities

- AFRPL — 1972 – Inhouse (Project Outgrowth Report) & Contracted Efforts – TRW, PSI
- NASA — 1972 – NASA Lewis Inhouse & Contracted Efforts – PSI, Lockheed, Rocketdyne
  - 1977 – NASA Marshall Inhouse & Contracted Efforts – PSI, U.S. Army Micom, Lockheed, BDM, UTSI, UAH
  - 1977 - JPL – System Studies – Lockheed, Boeing
- DARPA — 1977 – AVCO Everett Study
- AFOSR — 1983 – Contracted Efforts – Penn State, PSI, UTSI, U. of Illinois
- SDIO — 1986 – LLNL Inhouse & Contracted Efforts – AVCO, Spectra Technologies, NRL, PSI, RPI

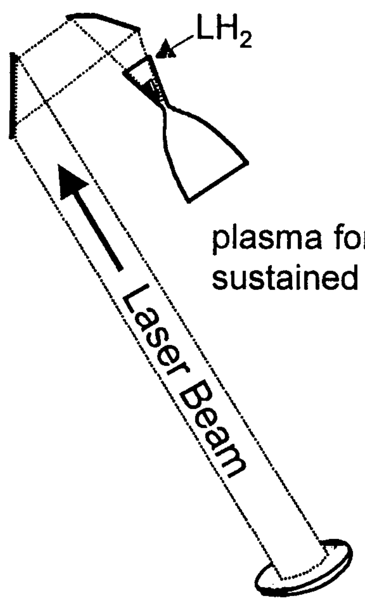
Major Laser Propulsion Funding Agencies and Contractors
The Early Years: 1972-1990

Funding ↓ / Contractors →	Physical Sciences Inc.	AVCO Everett Research Lab. Inc.	Mathematical Sciences NW Inc.	Lincoln Lab.	Lockheed Missiles & Space Co.	TRW	Rocketdyne	Lawrence Livermore Natl. Lab.	SRI International	Tennessee Space Institute	United Technology Research Ctr.	U. of Illinois	Photonic Associates	Hughes Research Lab	JPL	Redstone Arsenal	Aberdeen Proving Ground	Harry Diamond Lab.	Battelle Lab.
AF Rocket Propulsion Lab.	80/81					75/76					77/79								
AF Office of Scientific Research	83/84									85/91		87/88							
SAMSO (Los Angeles AF Station)		73																	
NASA/MSFC	78/80				78														
NASA/LEWIS	74/77	76	79		76/78		75/77						74/75						
NASA/JPL														75	84				
DARPA (ARPA)	76/82	74/78	75	76					76/77		73/74								73/75
US Atomic Energy Commission								74											
US Energy Research & Dev.								75											
Army																77	74	75	
SDIO								87/90											

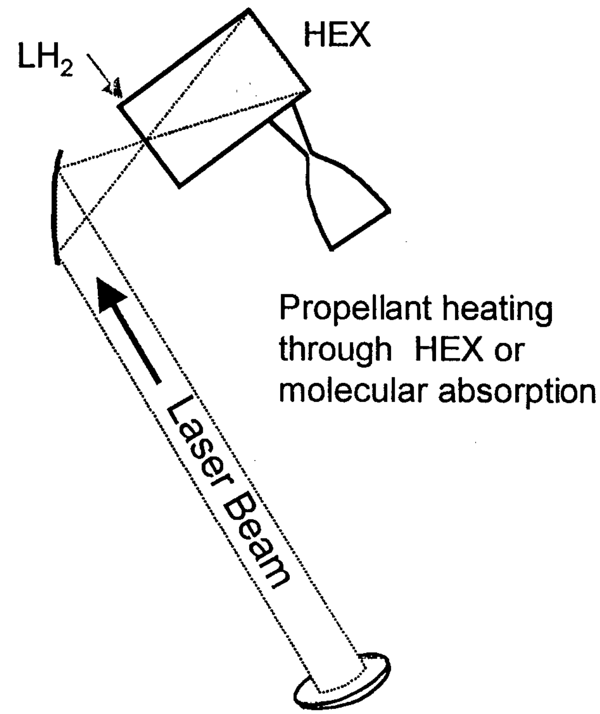
Laser Propulsion Interest During the Early Years



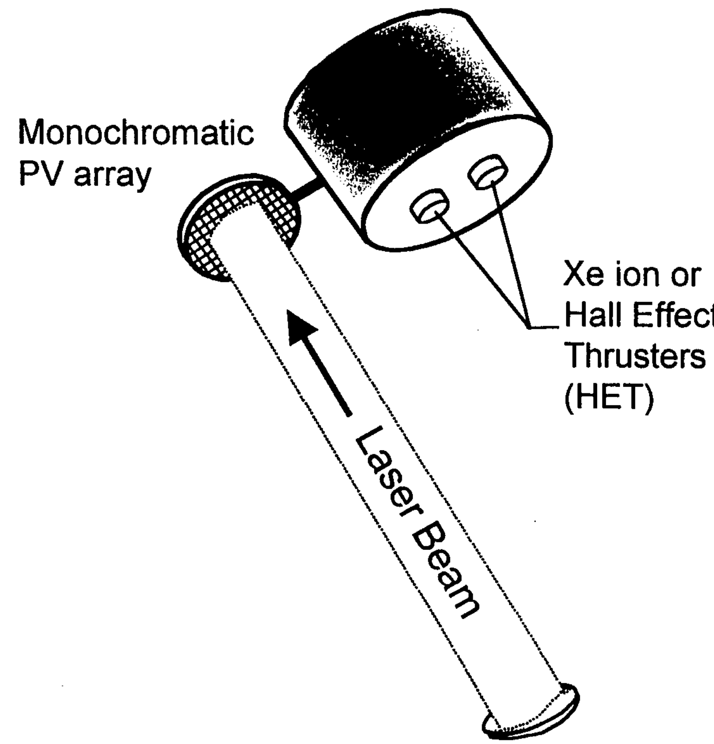
Laser Propulsion Concepts*



Laser Plasma
(Is = 1000 to 1500 sec)



Laser Thermal
(Is = 700 to 1100 sec.)

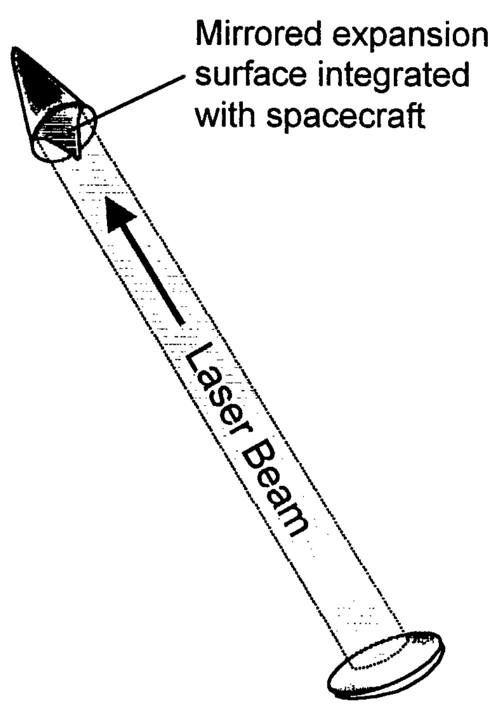


Laser Electric
(Is = 1200 to 4000 sec. at low thrust)

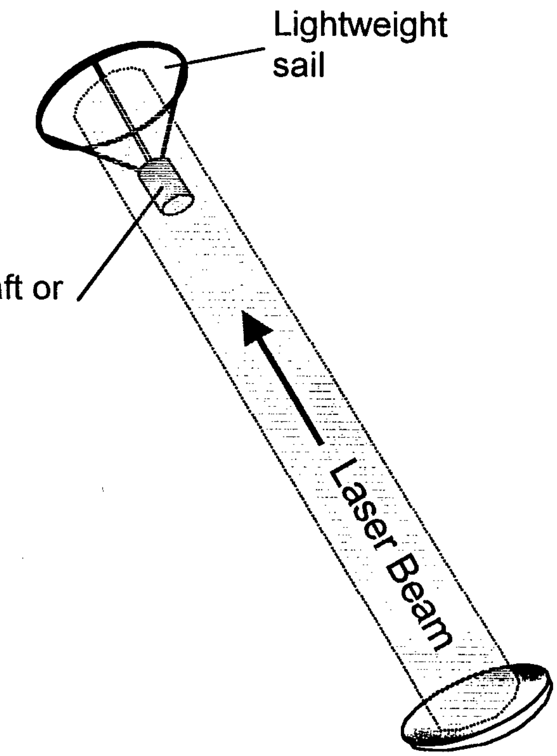
*Taken from Mr. Jim Shoji, Rocketdyne, Boeing Co.

Laser Propulsion Concepts* (cont'd)

Concluded



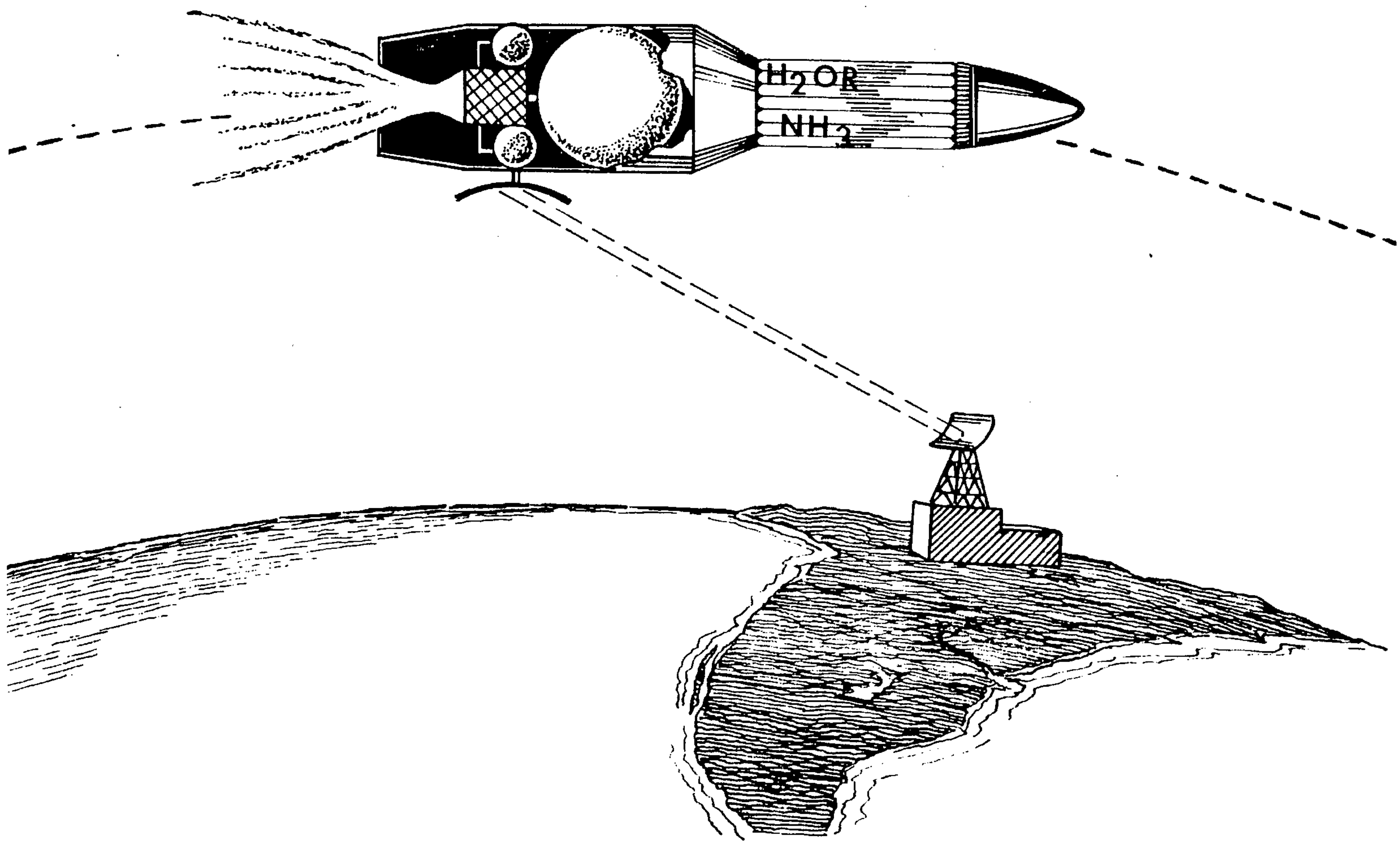
Laser Detonation
(Isp: Essentially infinity in air)



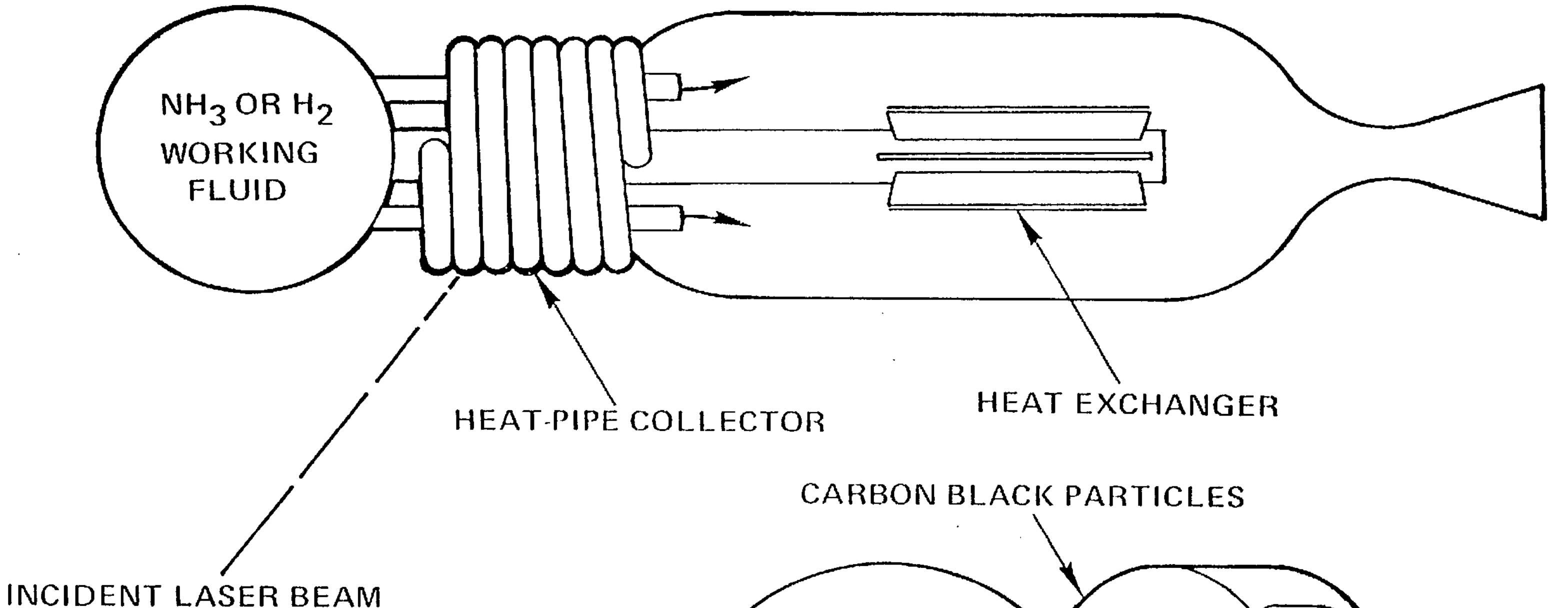
Laser Sail
(Isp: Essentially infinity)

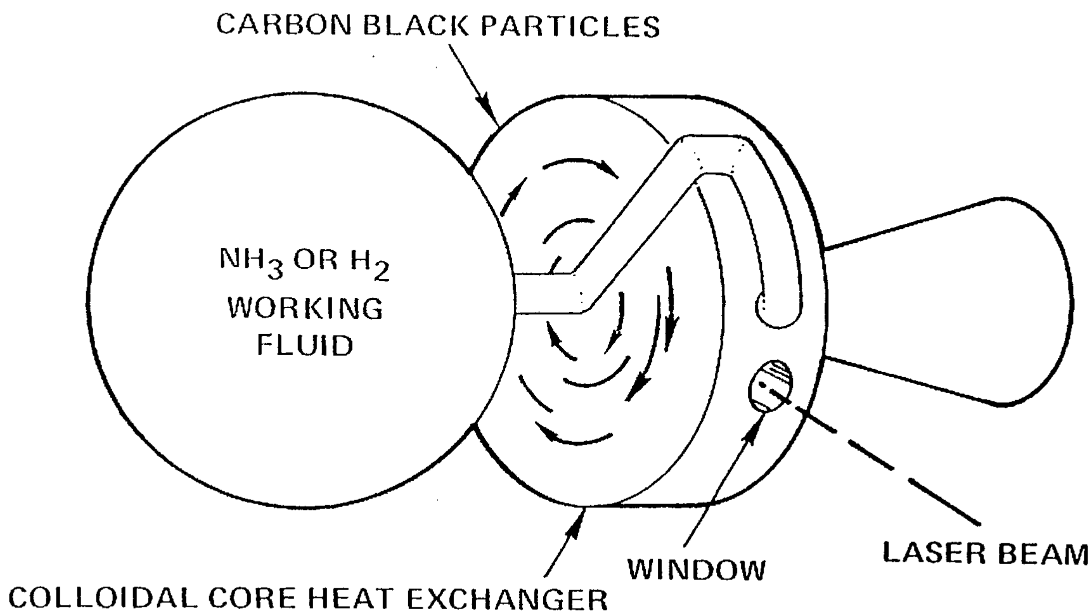
*Taken from Mr. Jim Shoji, Rocketdyne, Boeing Co.

Laser Propulsion (Project Outgrowth) (Circa 1970)

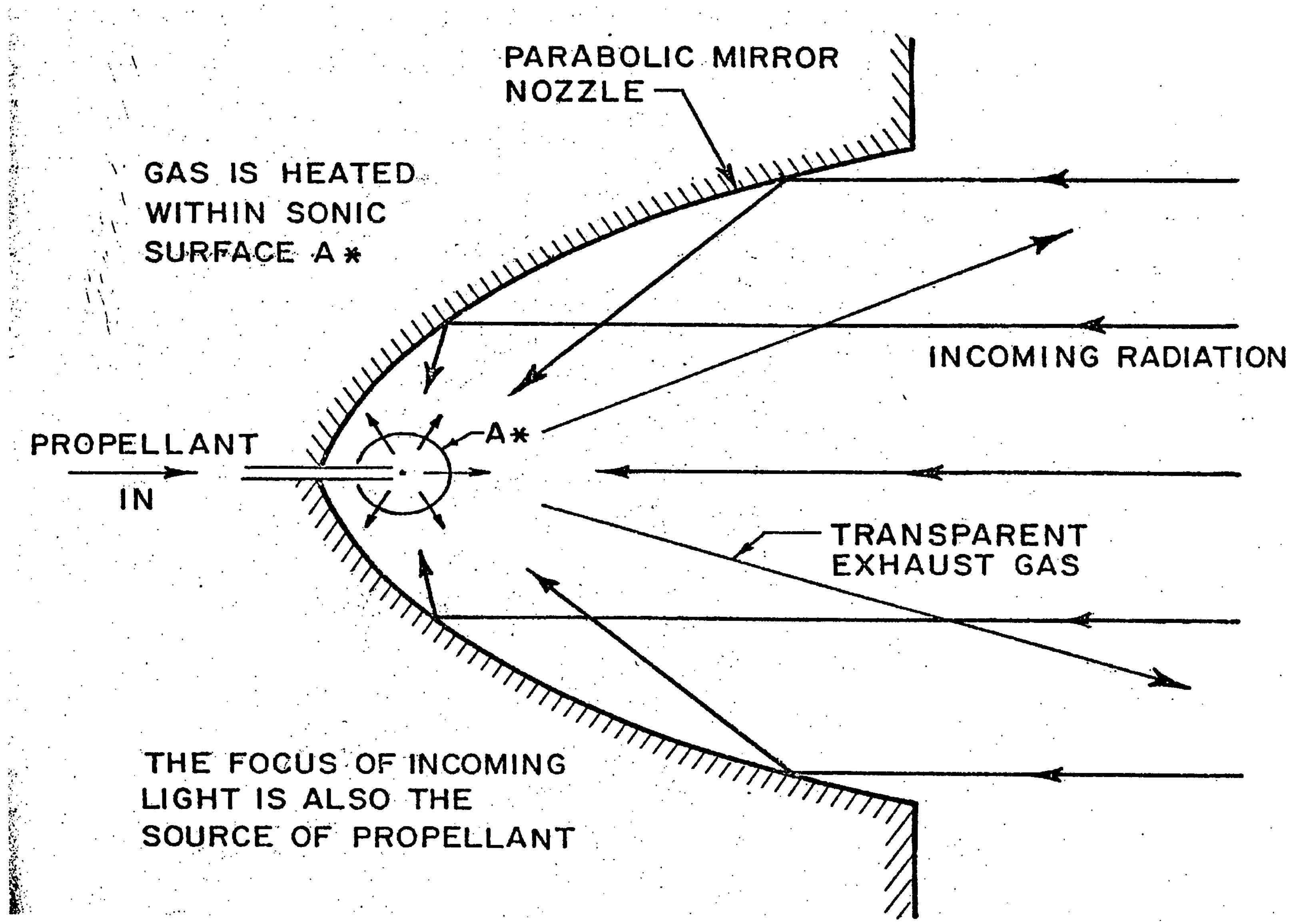


Laser Propulsion (Project Outgrowth) (Circa 1970)

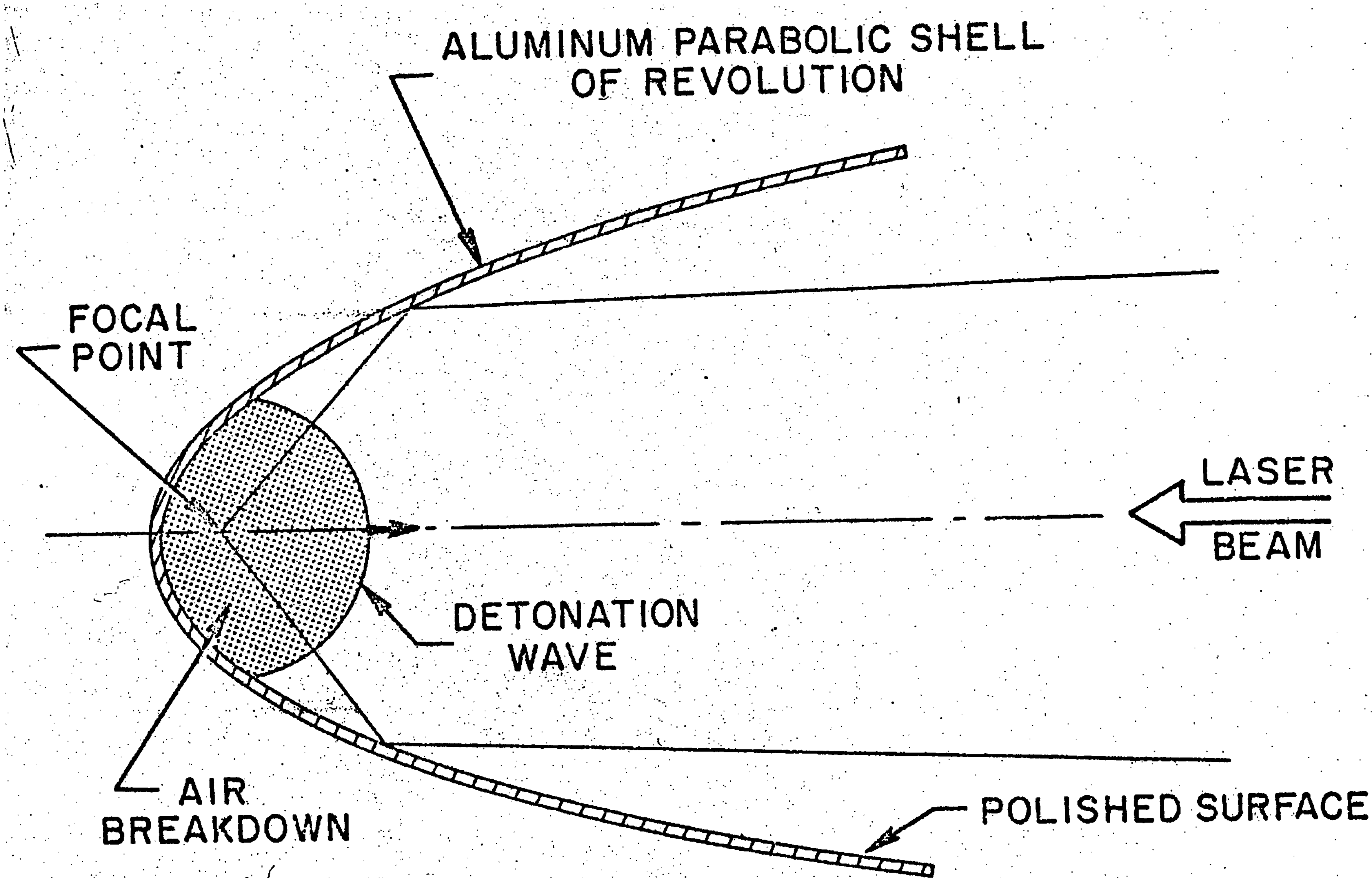




AVCO Liquid Propellant Rocket Using CW Laser (Circa 1973)



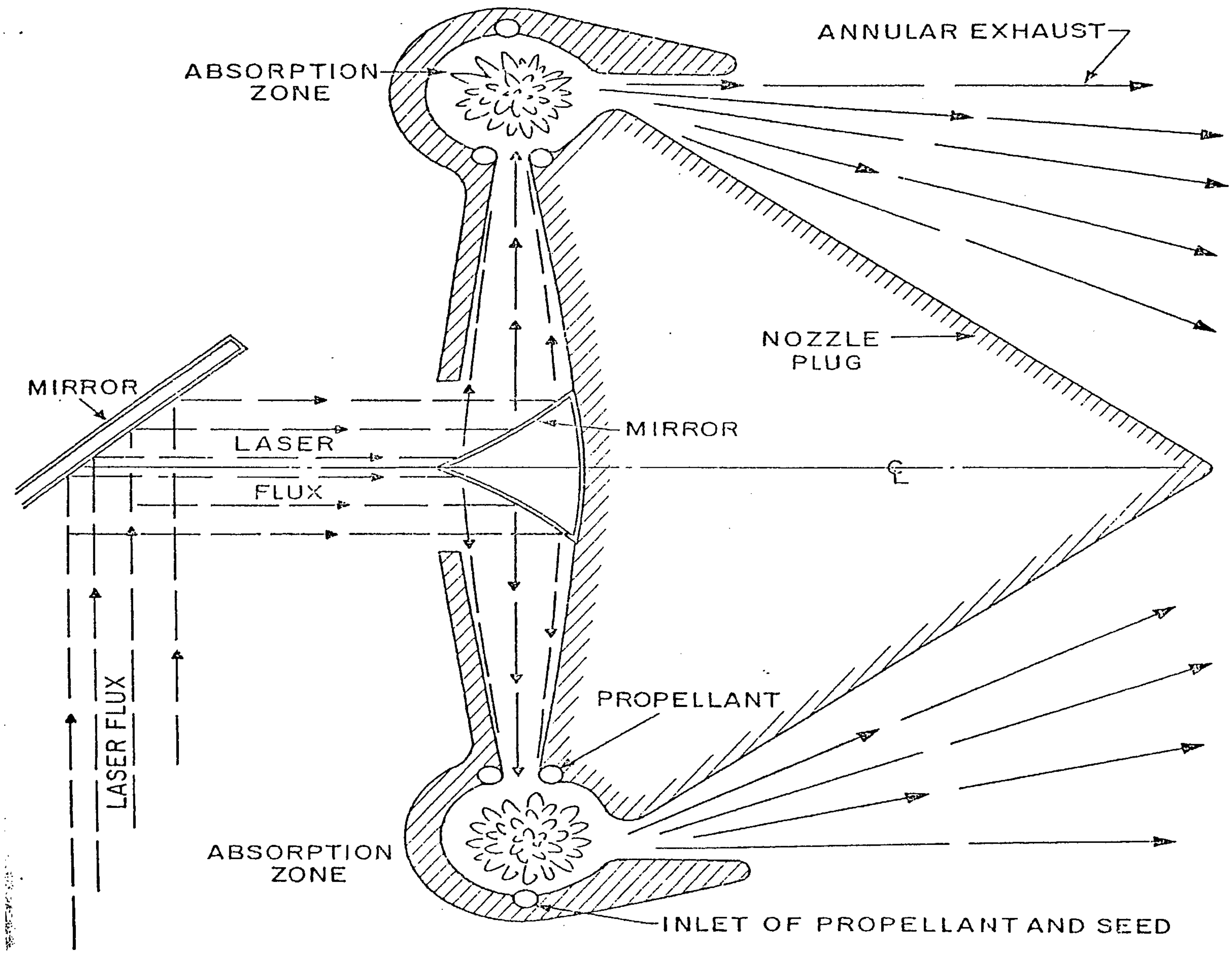
AVCO Laser Pulsejet
(Circa 1973)



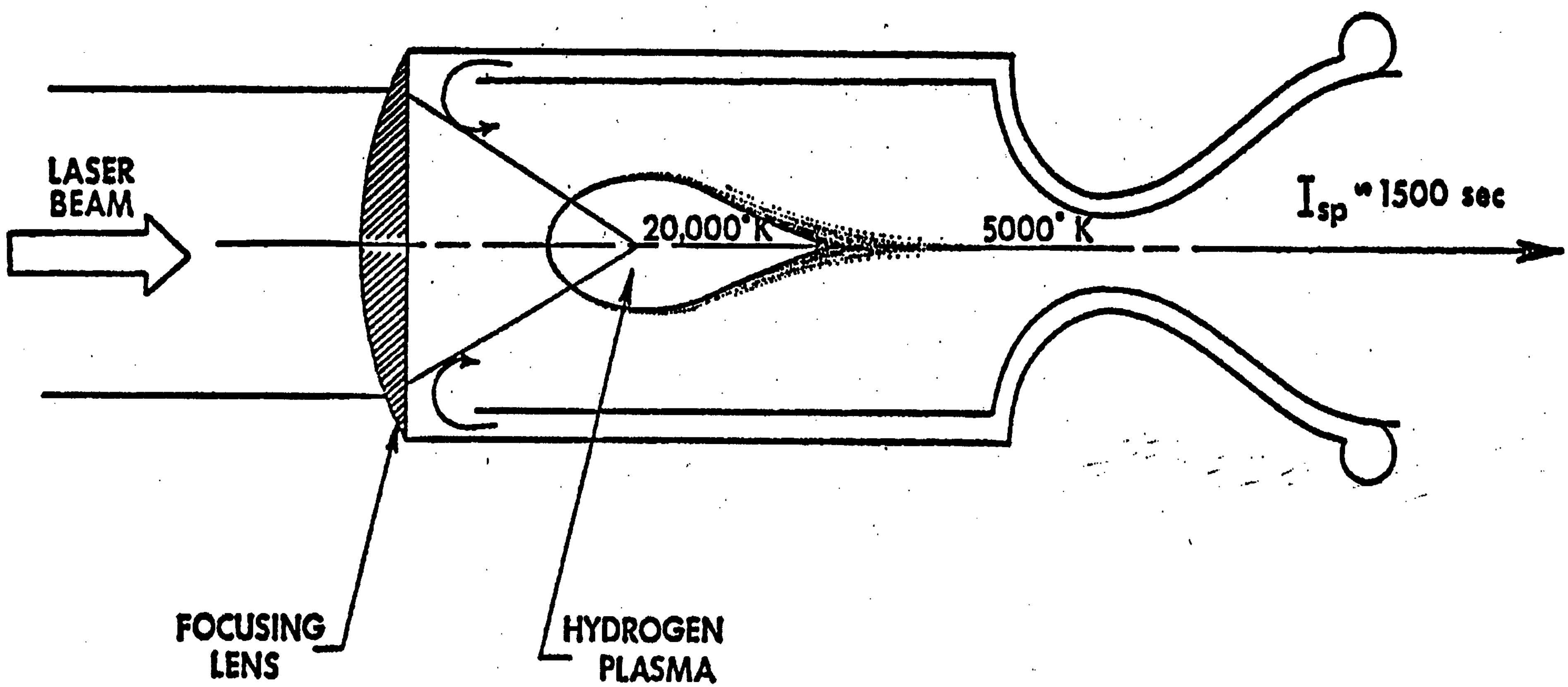
AVCO Advanced Laser Rocket

Toroidal Combustion Chamber, Plug Nozzle

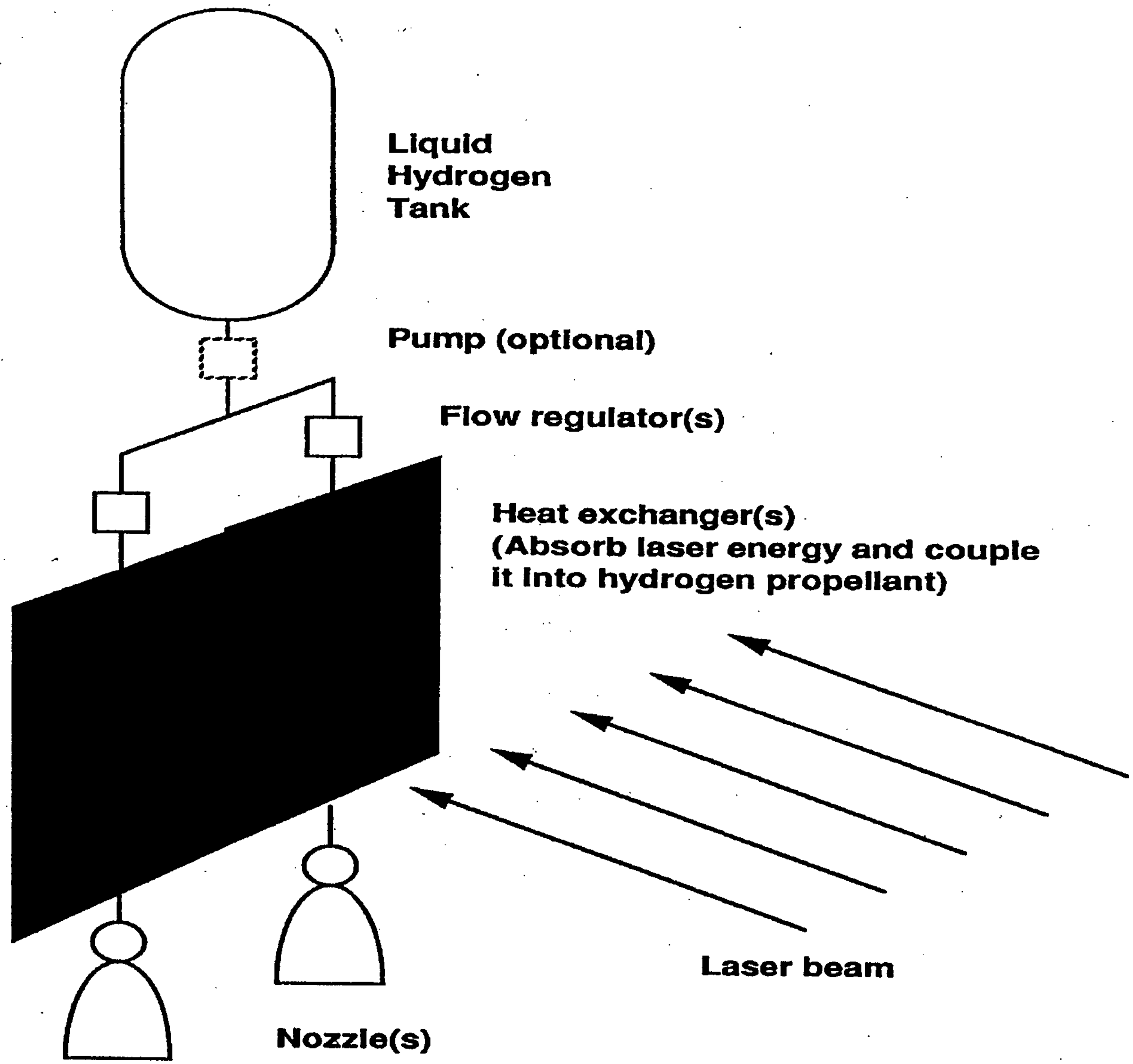
(Circa 1973)



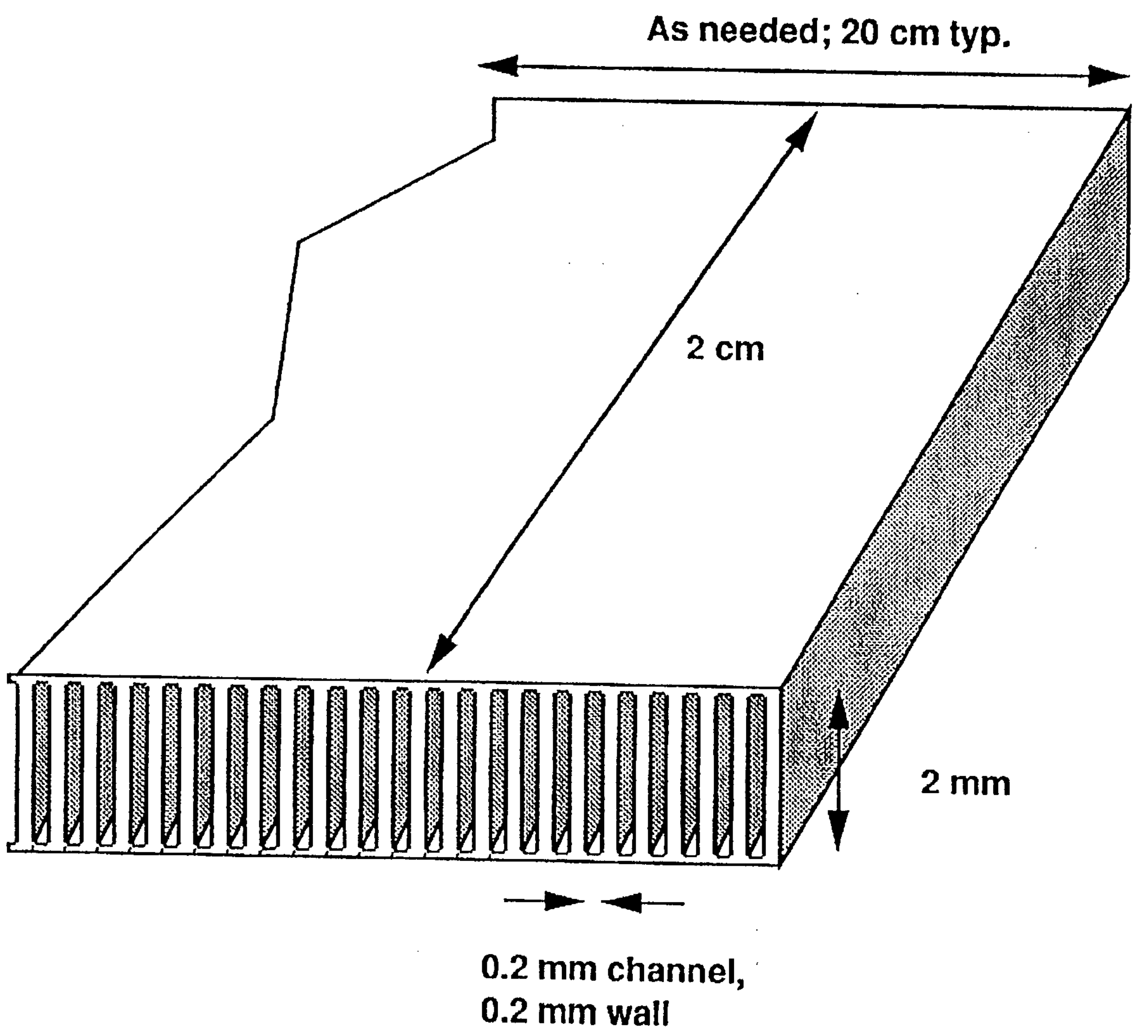
"Keefer" Laser Absorption Chamber
(Circa 1986)



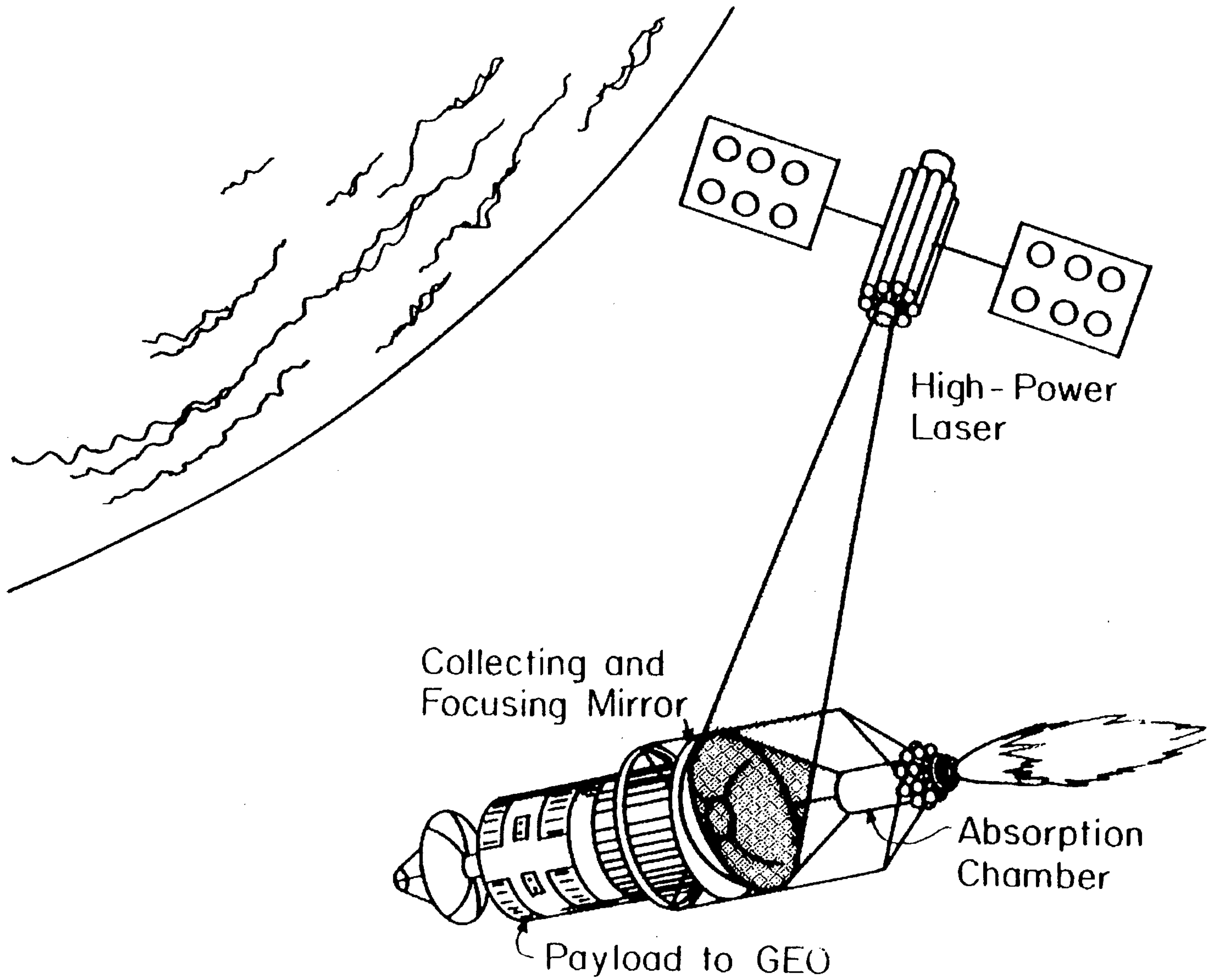
“Kare” Heat Exchanger Concept
(Circa 1992)



Kare's Microchannel Heat Exchanger Structure



University of Illinois Laser Propulsion Concept
(Circa 1987)



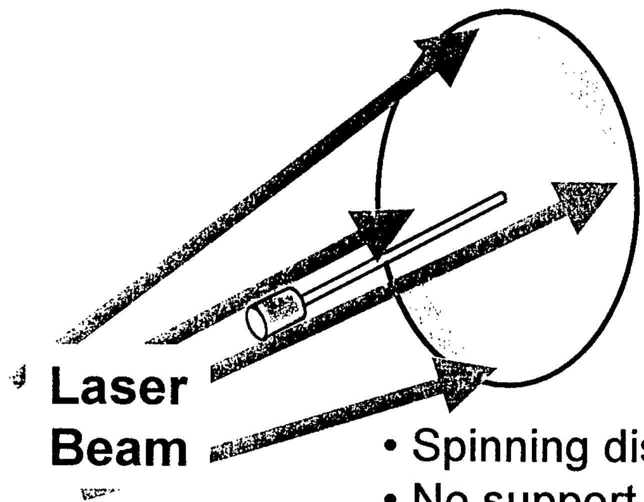
Laser Sail Propulsion

- **Features**
  - Large, lightweight structures
  - Very, very high power space-based laser
  - Low thrust and low acceleration
  - High spacecraft velocity potential (0.1 to 0.5c)
- **Performance Potential**
  - Specific Impulse : Infinite
  - Thrust : Dependent on laser power,flux, sail area, and efficiency

space after comma

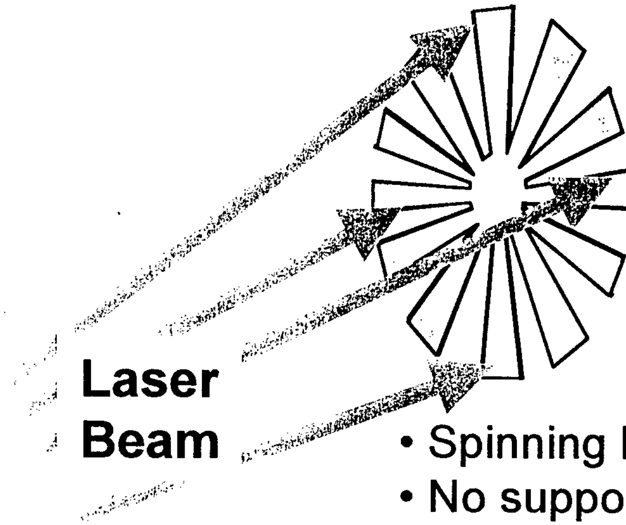
- **Technology Status**
  - Concepts developed
  - Synergistic with solar sail technology
    - Russian solar mirror ZNAMIA deployed in space (1993)
    - On-going NASA/JPL efforts
    - Other university/small group/industry activities
- **Issues**
  - Very, very high power space-based laser
  - Fabrication and deployment of very large structures (lens and sail)
  - Verification of multi-function laser sail sections

Laser Sail Design Concepts



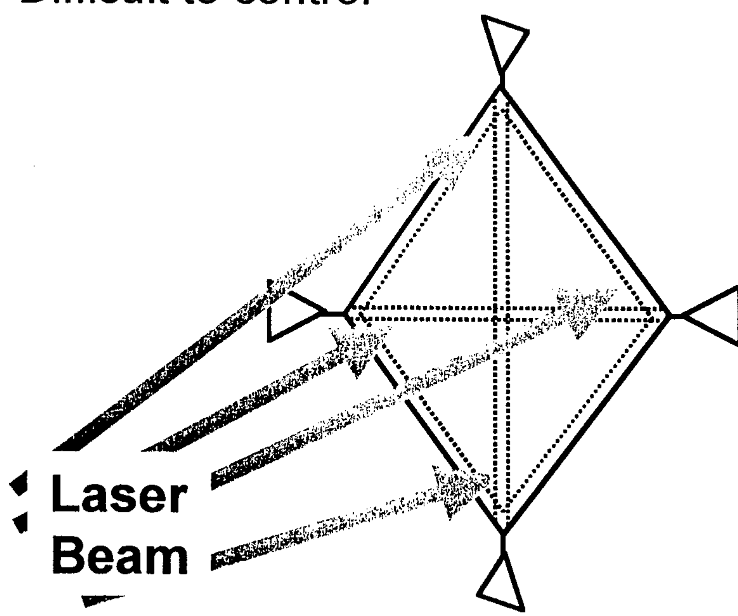
Disc Sail

- Spinning disc
- No support structure
- Difficult to control



Heliogyro Sail

- Spinning blades
- No support structure
- Control by pitching blades



Rectangular Sail

- Non-rotating
- Structurally supported
- Control - solar pressure vanes

Developments in the 90's

- NASA/MSFC
  - Financially Contributed to the Air Force program during FY 97 & 98.
  - Initiated their own program in FY 99
    - FY 99 Study Phase
    - Initiated Testing in FY 2000
    - Concepts include parabolic pulsejet, Lightcraft, & "Phipps" laser concept.
- Air Force
  - Lightcraft Development Program Started FY 96
  - The AFRL and NASA/MSFC have a Memorandum of Agreement (MOA) to work together on the Lightcraft.
- German parabolic pulsejet tests conducted in 1999.

Laser Propulsion At MSFC

By

Mr. Sandy Kirkindall

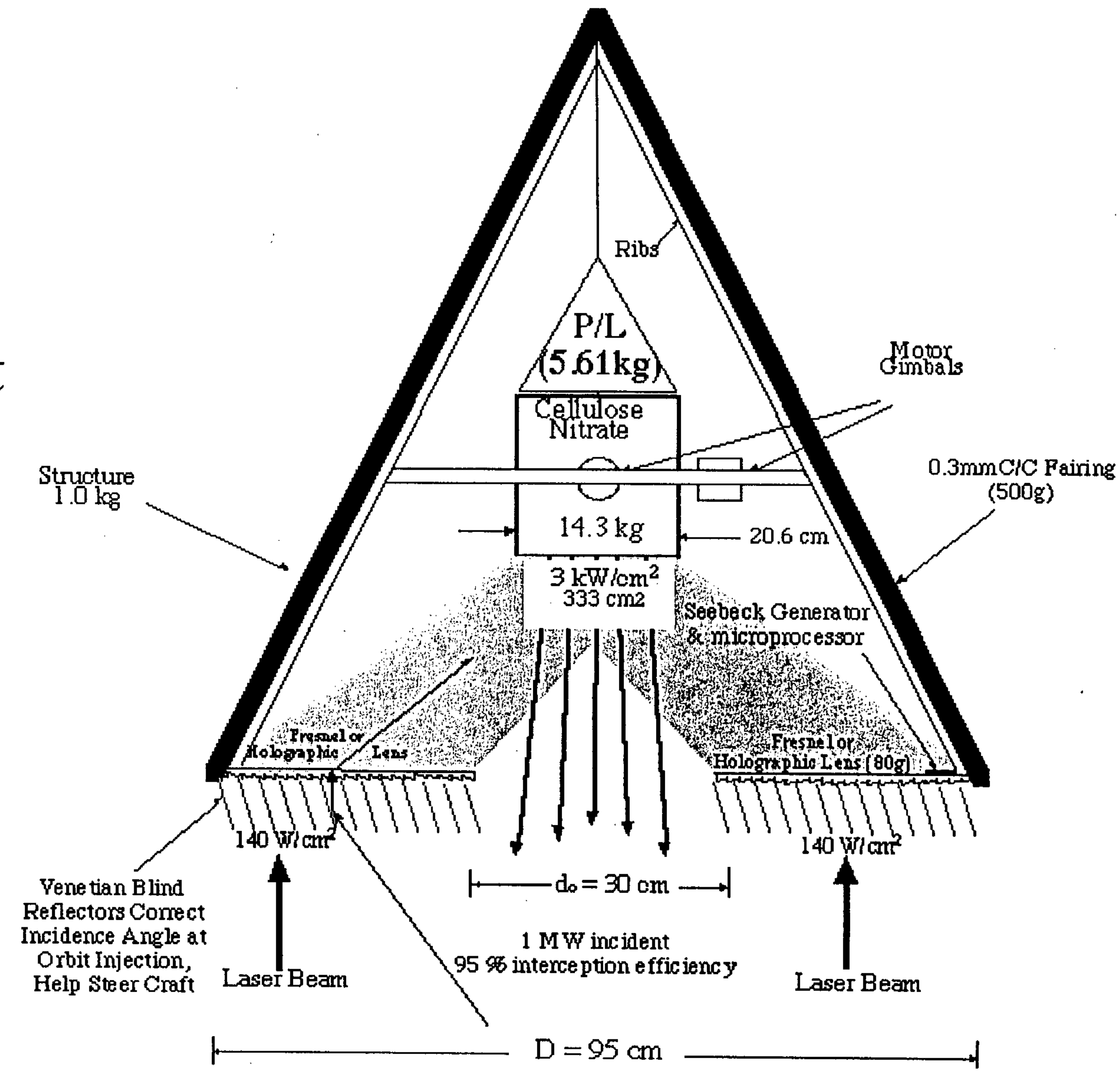
NASA/MSFC, TD40

Bldg. #4666

Huntsville AL 35812

Phipps/NASA Design

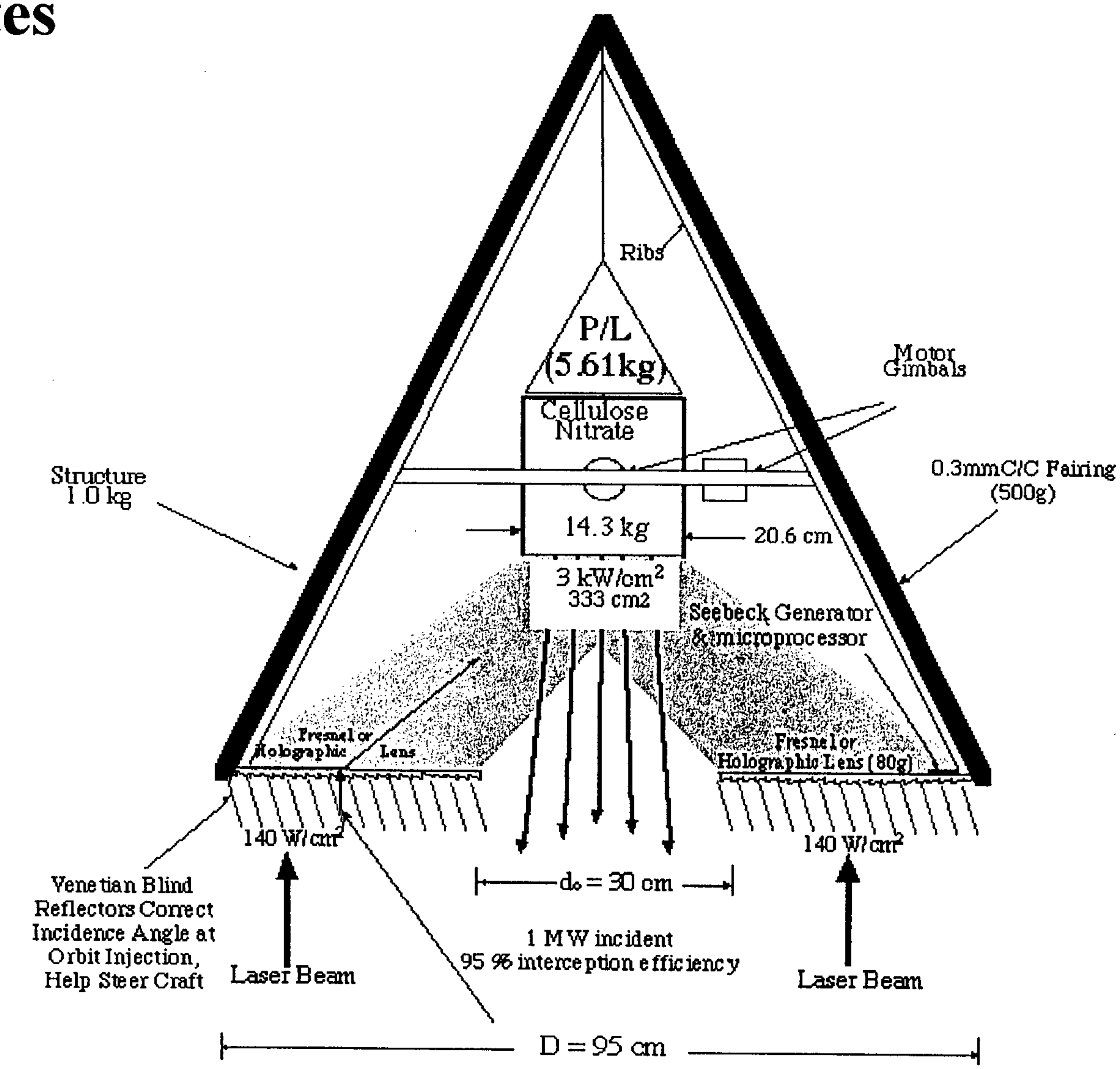
- D/L=1 optimizes
  - Drag
  - Center of thrust
  - Jet/lens clearance
- Heat shield dumped at 120km
- "Venetian blinds"
  - For orbit insertion
  - For partial steering



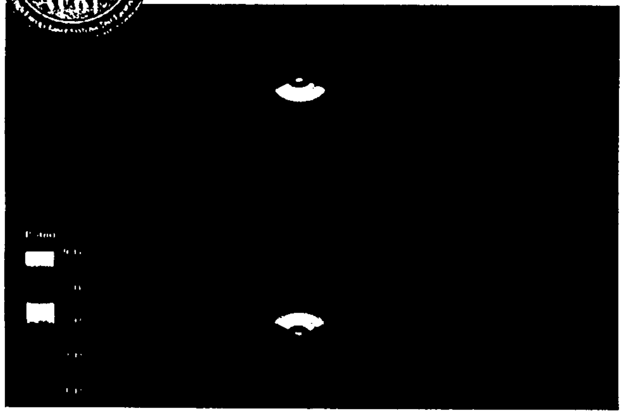
Phipps/NASA Design (Cont)

Concluded

- Fresnel lens concentrates light
- Seebeck generator provides 100W system power
- space or dash? µprocessor controls actuators



NASA CFD Studies of Lightcraft Pulse Dynamics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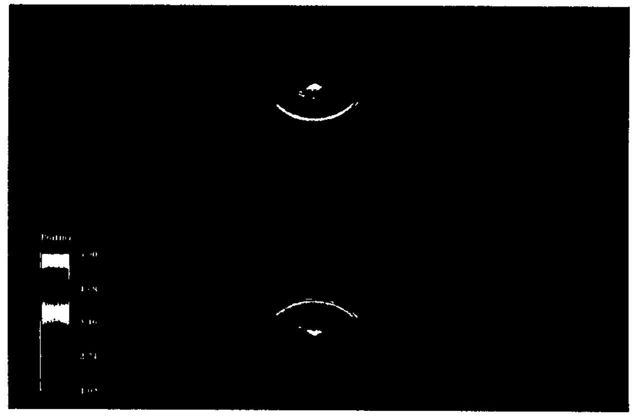
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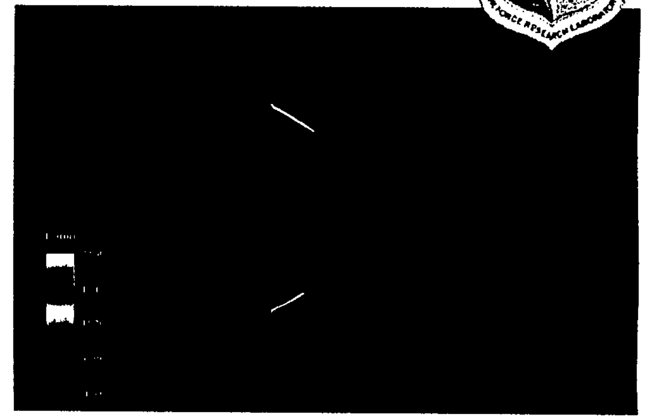
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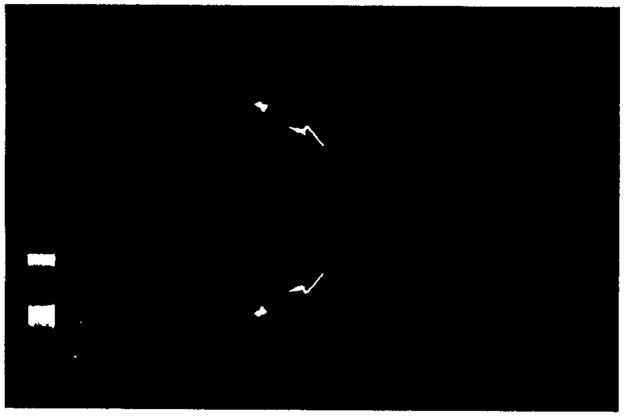
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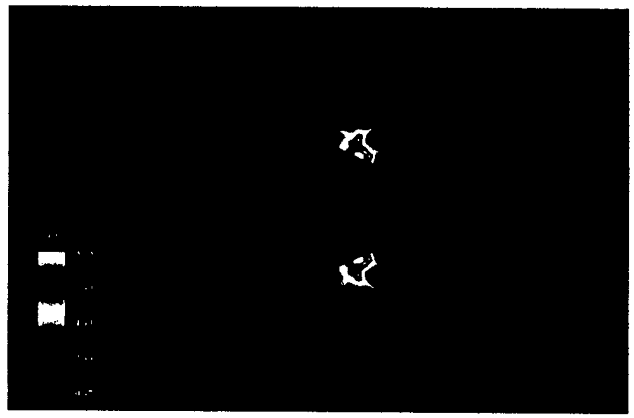
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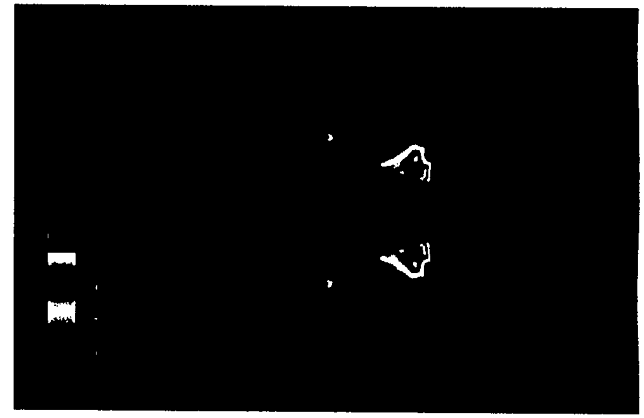
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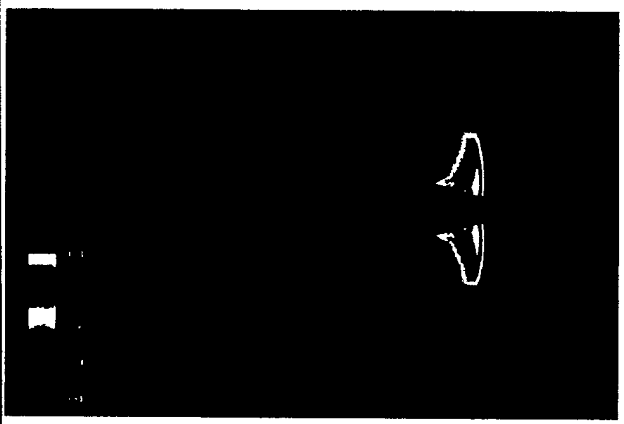
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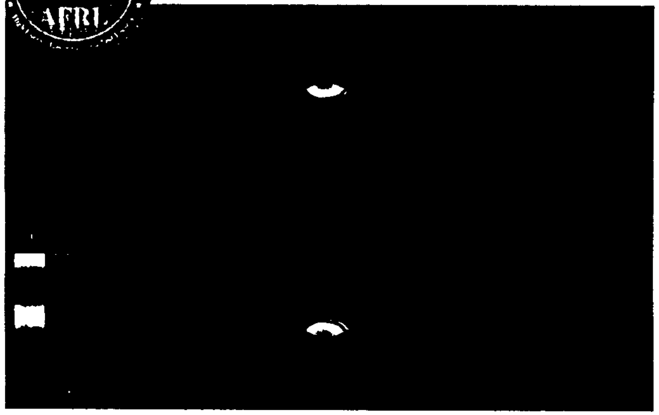
PRESSURE (ATM)

NASA CFD Studies of Lightcraft Pulse Dynamics



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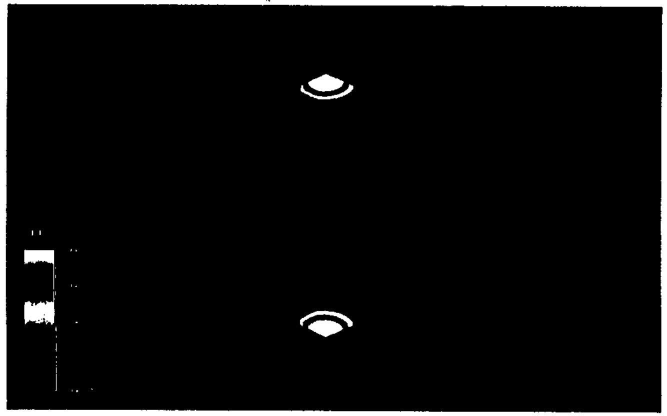

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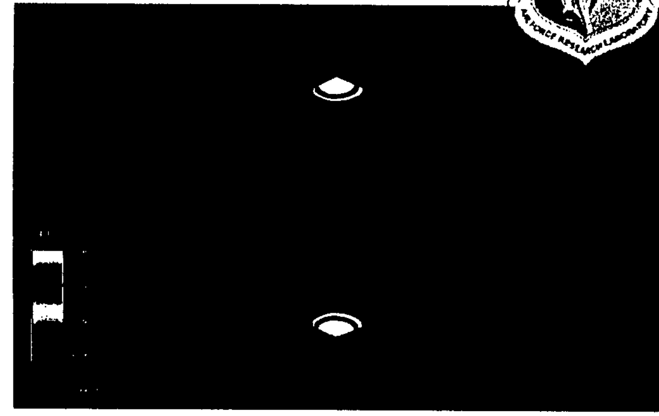

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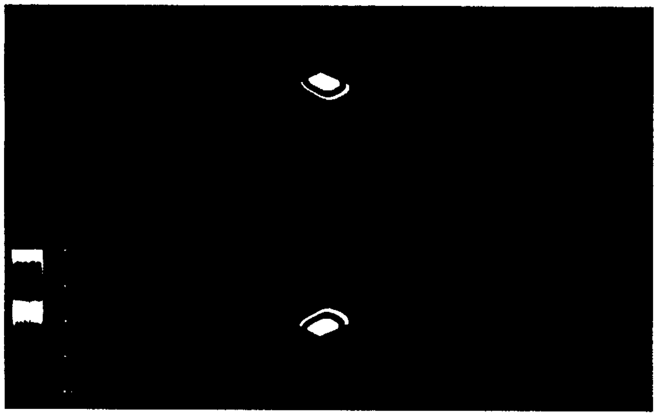

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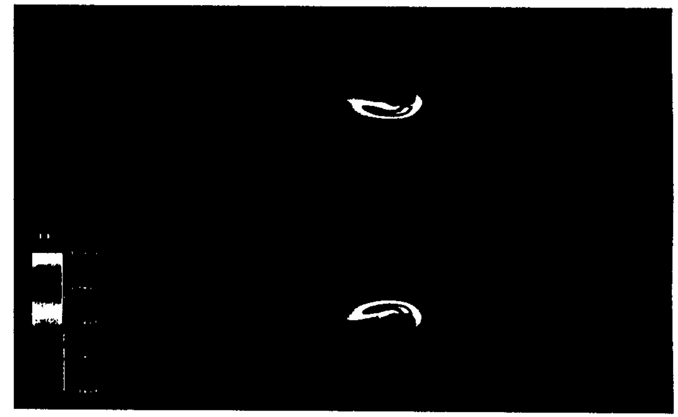
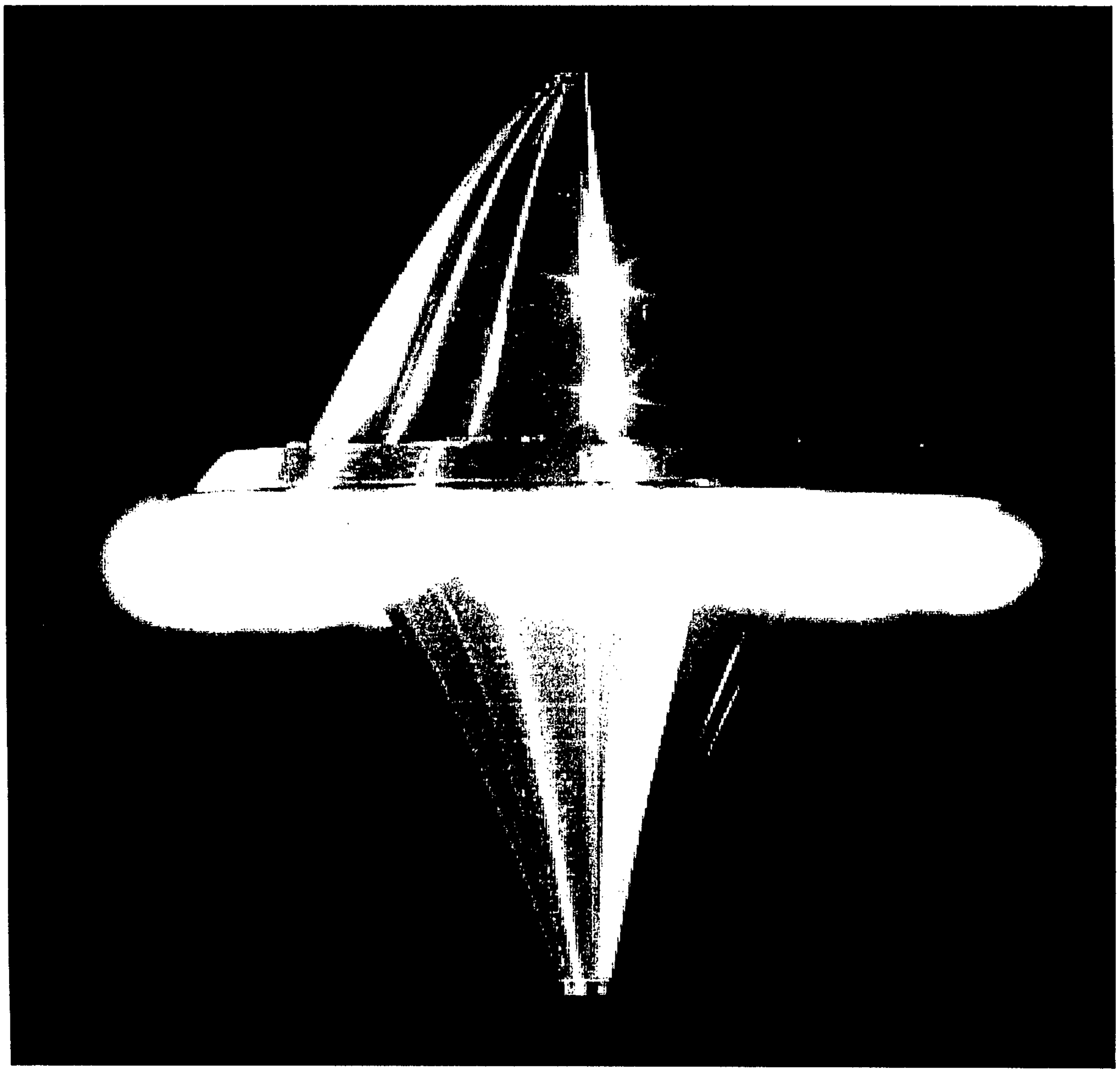


80 usec

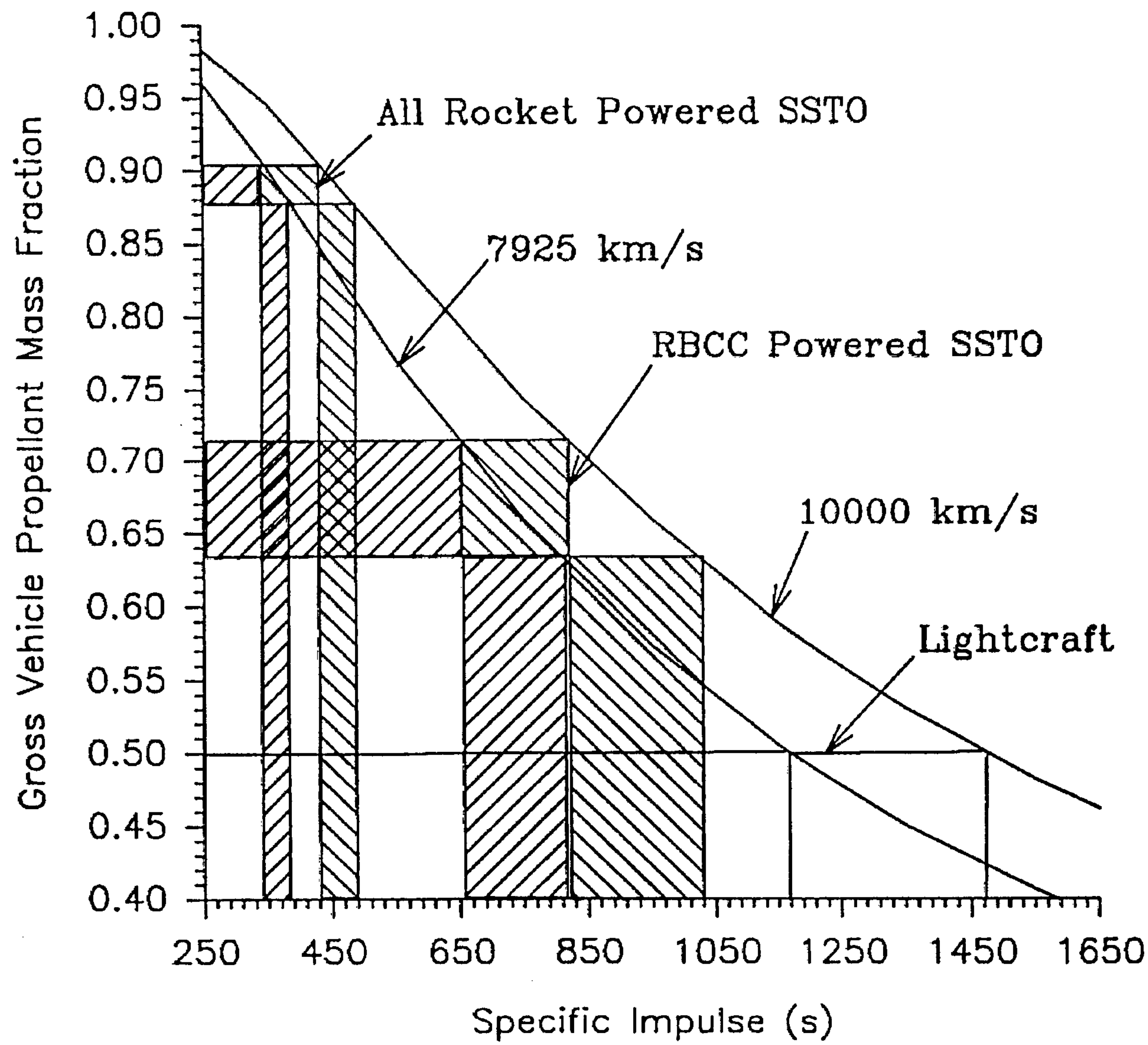
122 usec

TEMPERATURE (K)

LASER LIGHTCRAFT DEVELOPMENT PROGRAM



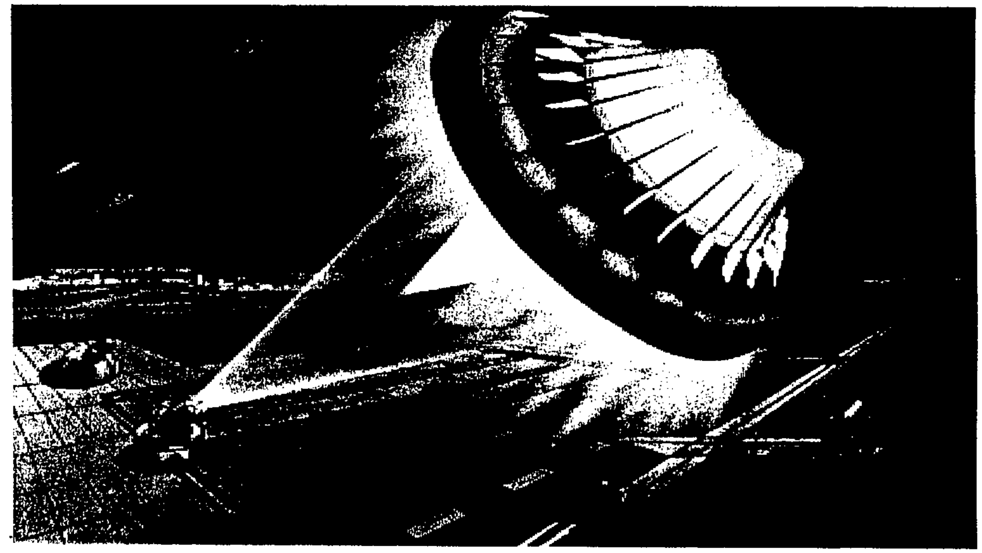
The "Rocket Equation" Applied to Single-Stage-to-Orbit (SSTO) Space Transportation Concepts



LOW COST ACCESS TO SPACE

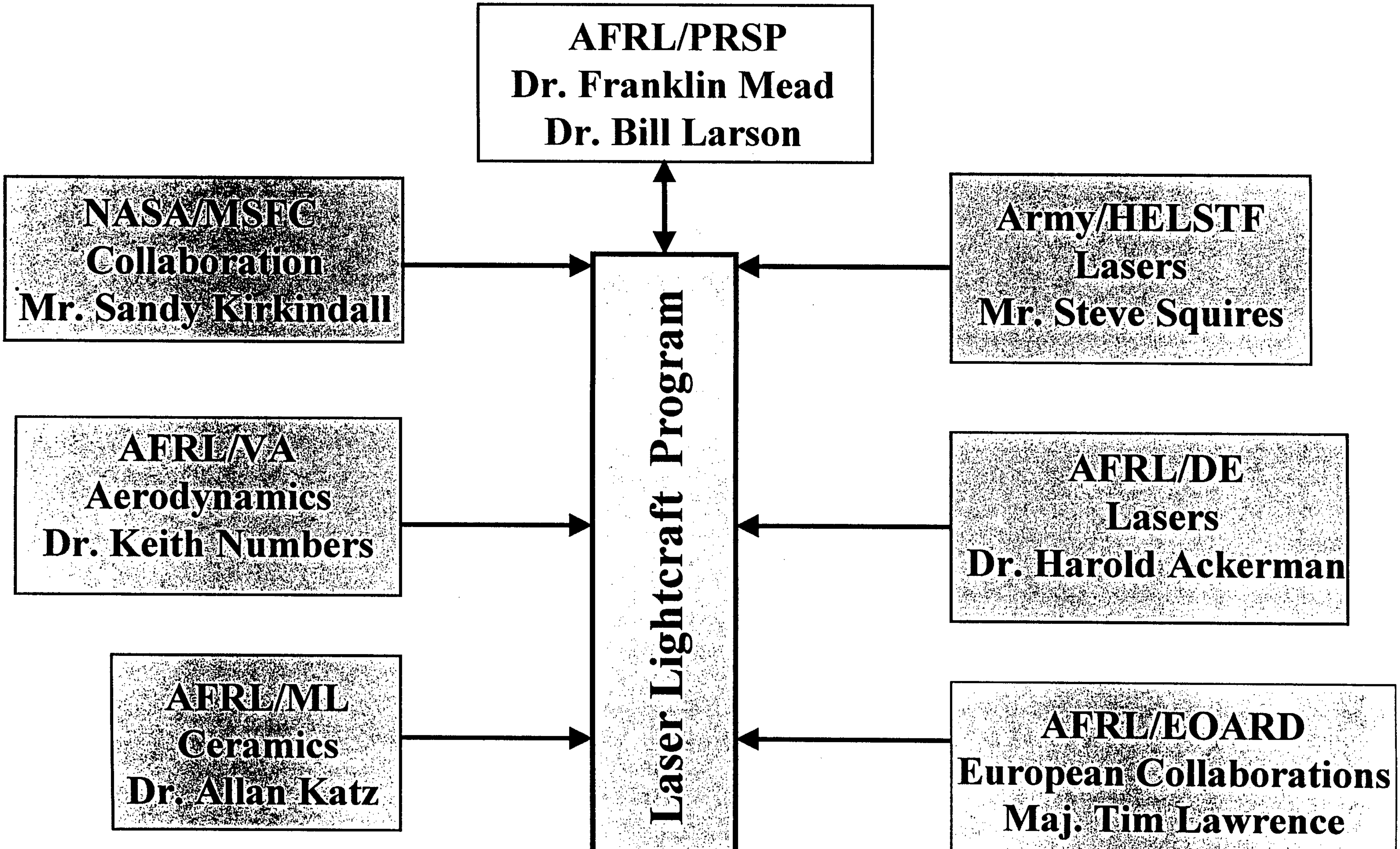
Unique Features

- Laser-Propelled Beam Rider
  - Decoupled Energy Source (1 MW class infrared G/B laser)
  - Single-Stage-to-Orbit (~2 kg initial weight; Mf=0.5)
  - Very High Isp (Airbreathing to M=5 at 30 km; 1,000 to 3,000 s in space with H2)
  - Combined-Cycle Pulsed Detonation Engine

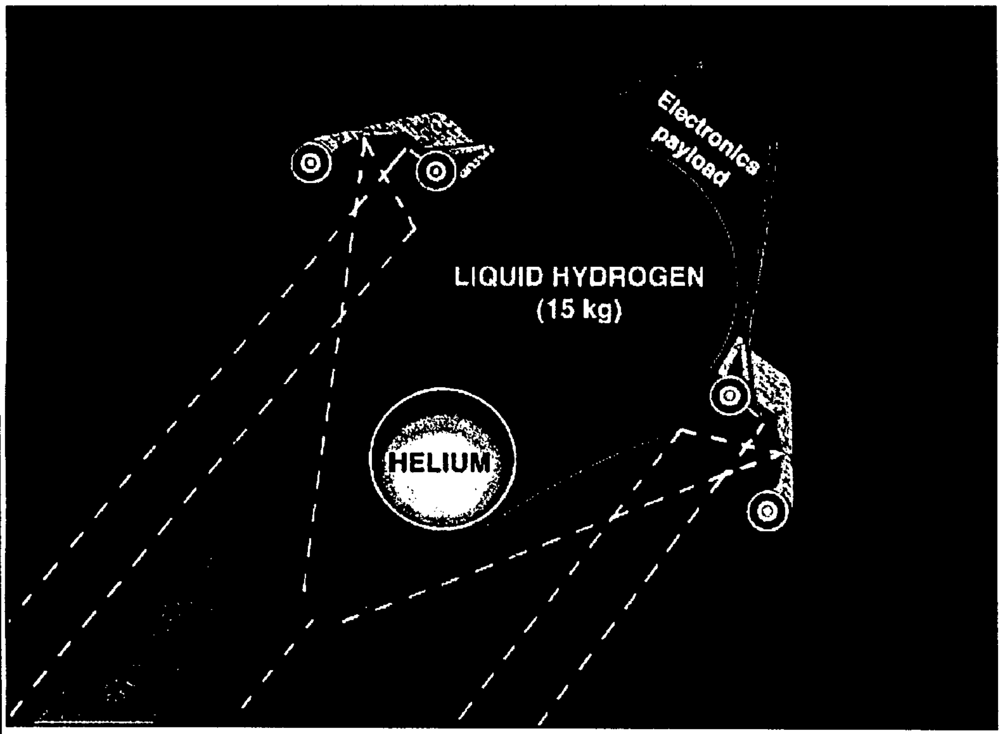


- Multiple/Shared Functional Components
- One-Meter Diameter Parabolic Telescope (Resolution=8 to 15 cm from LEO)
- Simple Reliable Safe
- Simplicity, Reliability, Safety, Environmentally Clean
- High Launch Rate (All azimuth, On-demand)
- Less Than $500 of Electrical Power For Launch to LEO

Program Alliances



The Lightcraft Concept



- Three Main Components
  - Forebody Aeroshell (External Compression Surface)
  - Shroud (Air Inlet & Impulsive Thrust Surface)
  - Afterbody (Parabolic Mirror & Plug Nozzle)
- Tankage
  - Liquid Propellant (LN2, NH3 or LH2)
  - Helium Pressurant
- Nanosatellite (1 kg & 1 m Dia. Focus Telescope)
- Electronics in Forebody
- Reentry Capability
- Solar Powered in Orbit

APPLICATIONS

- Nanosatellite “low cost” launch-on-demand
  - Air Force, NASA, BMDO, Communication Industry
- High Resolution Imaging, Surveillance, and Mapping (~~i.e.~~ e.g., Earth Resources)
- Global Positioning and Tracking
- Threat Detection and Tracking
- Astronomical Telescope (~~i.e.~~ e.g., Amateur & Professional)
- Communications and Relay (~~i.e.~~ e.g., Cellular Phone)
- Tactical Laser Propulsion (~~i.e.~~ e.g., Hypersonic KKV)

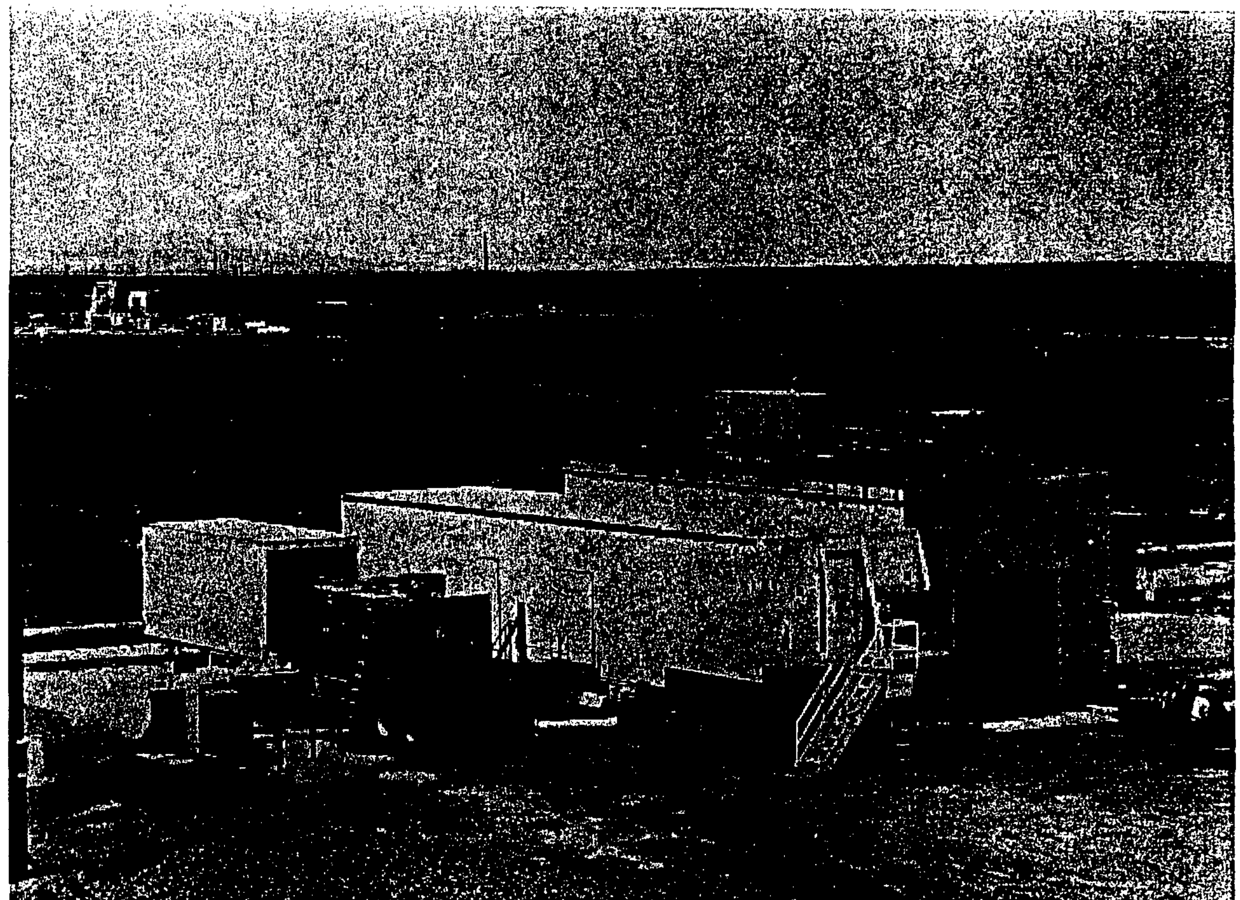
Lightcraft Development Objectives

- Broad Application Based Nano-/Microsatellites
  - All Azimuth, Launch-on-demand - don't need because it's not a complete sentence
  - Air Force, NASA, BMDO, NRO, Communication Companies, Private Industry, Individuals
- Near-term (7 yrs.)
  - Launch to LEO of 1 kg vehicles for less than $500 of electrical power, and less than $20K total cost
  - Meet a variety of NASA/AF/Industry requirements for low cost access to space
- Far-term (10 to 12 yrs.)
  - Launch 100 kg (220 lbs) AF/NASA vehicles to LEO for less than $1.5M*
  - Commercial laser launch services become viable contenders, as the lowest cost provider

* NASA requirement for Bantam-class payloads by FY 2006.

Pulsed Laser Vulnerability Test System (PLVTS)

- **Original Performance**
  - 800 joules/pulse
  - 10 Hz 30-sec ?
  - 30 :sec pulses
- **Modified Performance**
  - 1998
    - 400 joules/pulse
    - 28 Hz 18-sec ?
    - 18 :sec pulses
  - 1999
    - 150 joules/pulse
    - 30 Hz 5-sec ?
    - 5 :sec pulses

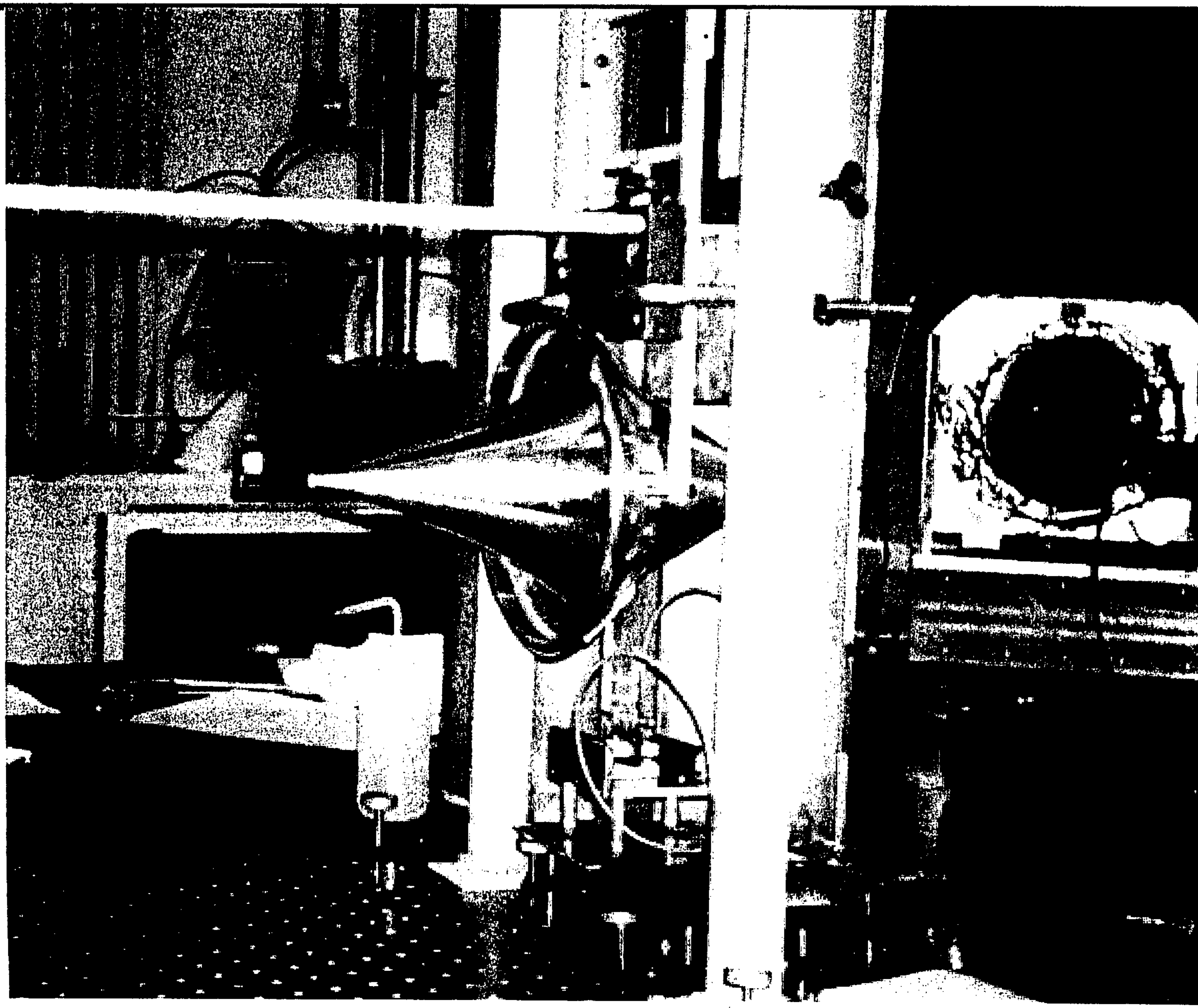


Phase I Accomplishments

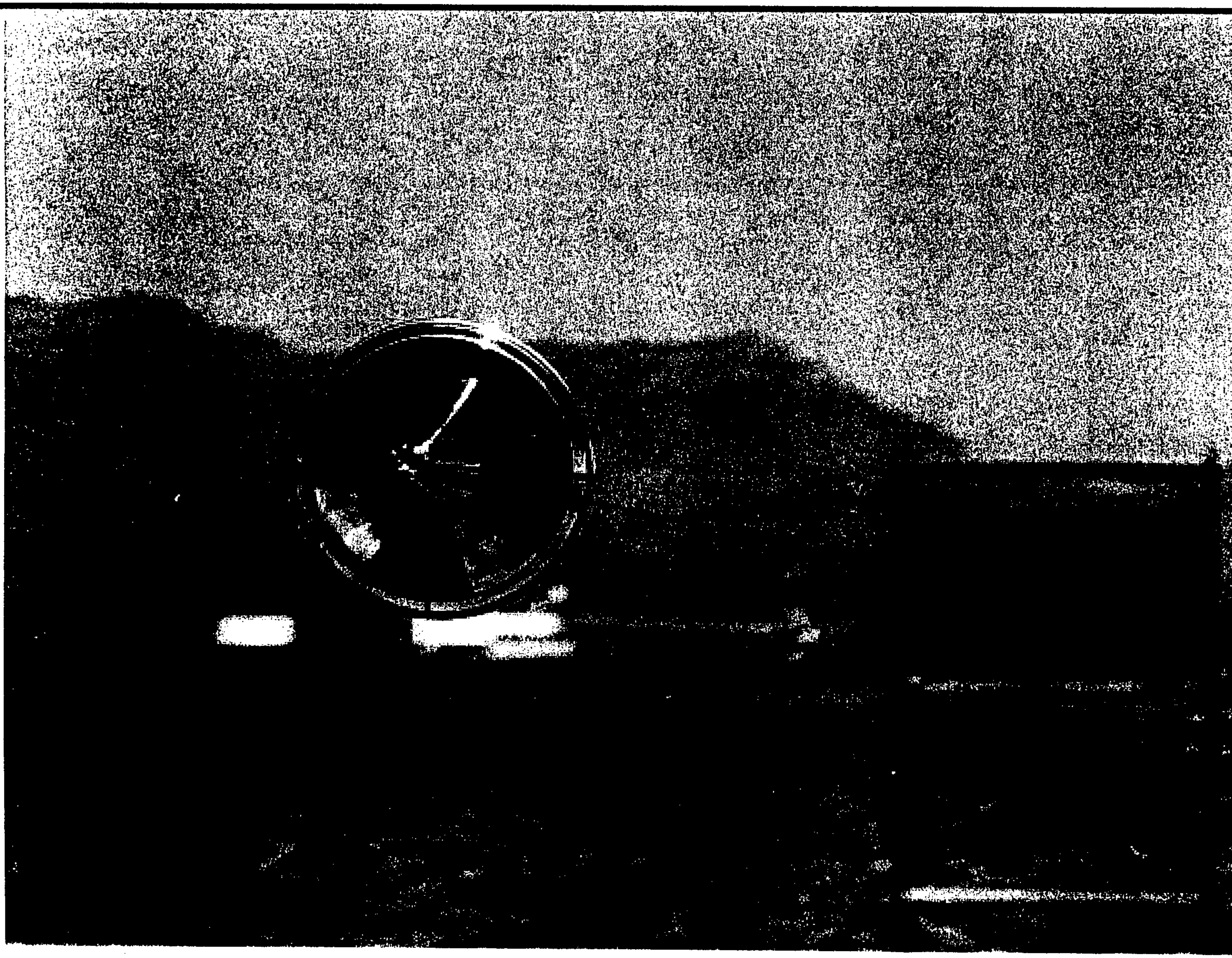
- **Phase I - Completed Dec 98**
  - A 3-Year Program To Demonstrate Concept Feasibility
  - Lightcraft Concept Feasibility Demonstrated By:
    - Impulse, thrust, and pressure measurements accomplished.
    - Shadowgraph, and beam propagation (to ~90 m) studies accomplished.
    - Lightcraft optics/engine vehicle geometry optimized.
    - Pointing & tracking system demonstrated on horizontal wire-guided flights to ~122 m.
    - Out door vertical free-flights to ~29 m accomplished.

one word

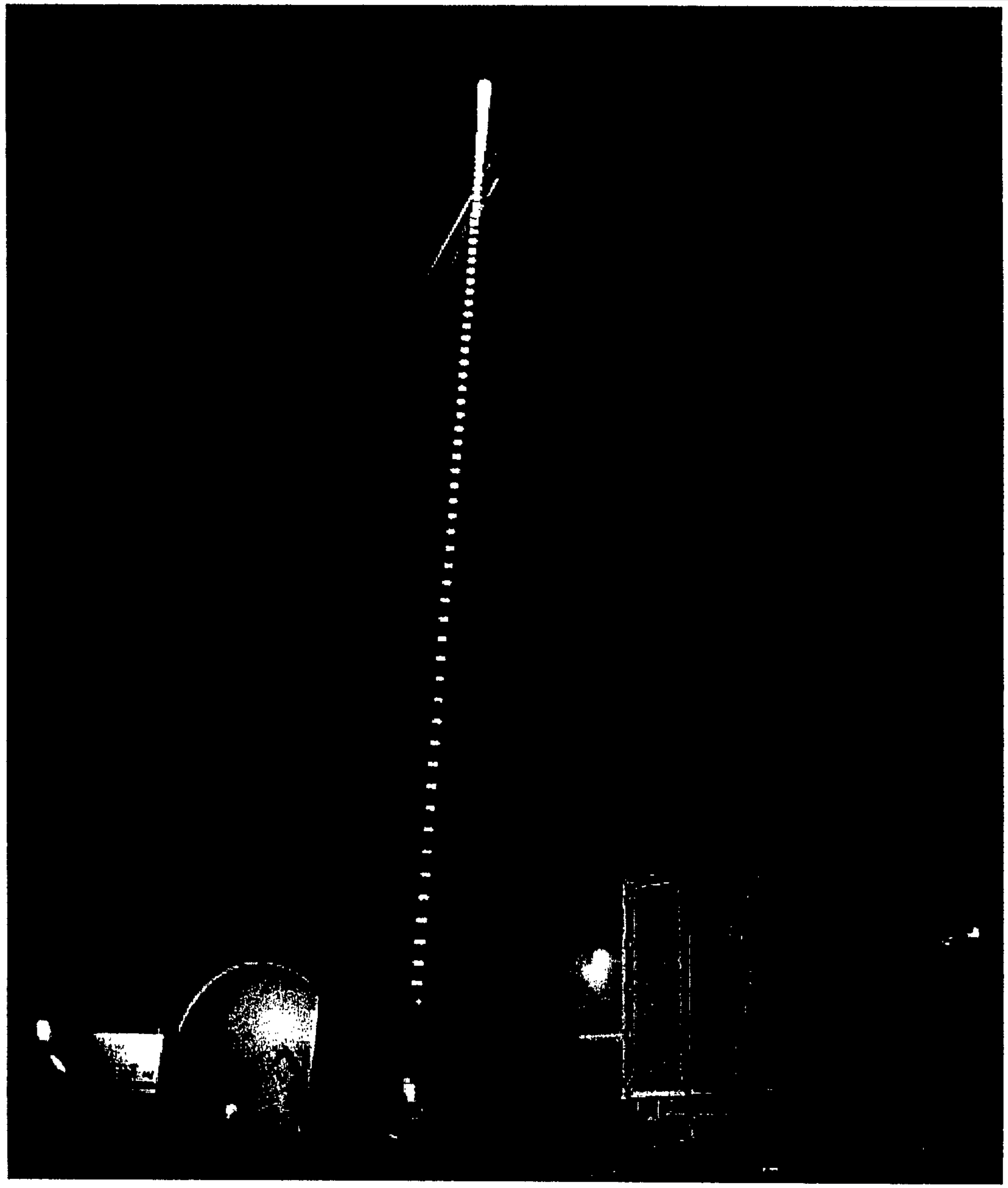
Lightcraft Mounted to Ballistic Pendulum "Impulse Stand"



FOUR-HUNDRED FOOT OUTDOOR WIRE TEST CONFIGURATION



29-Meter Outdoor Vertical Flight

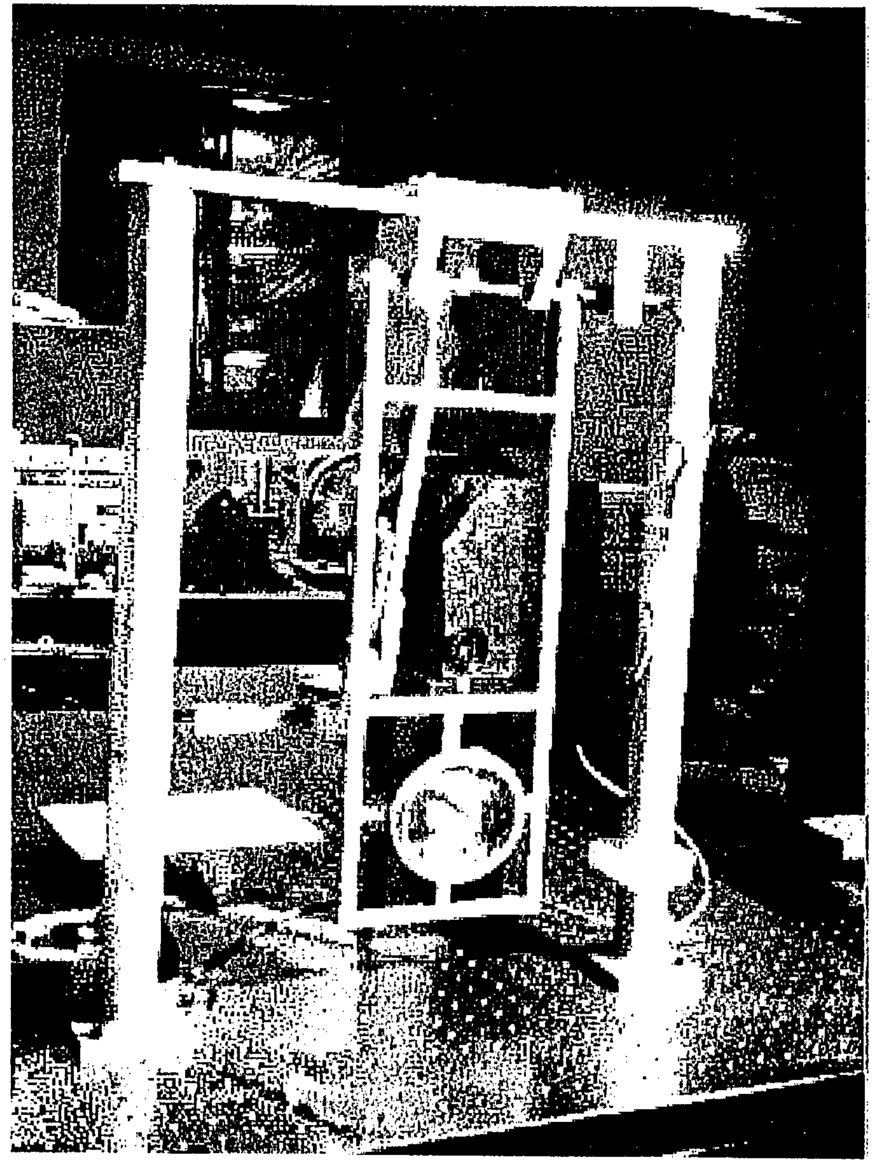


Model #200 Lightcraft Series

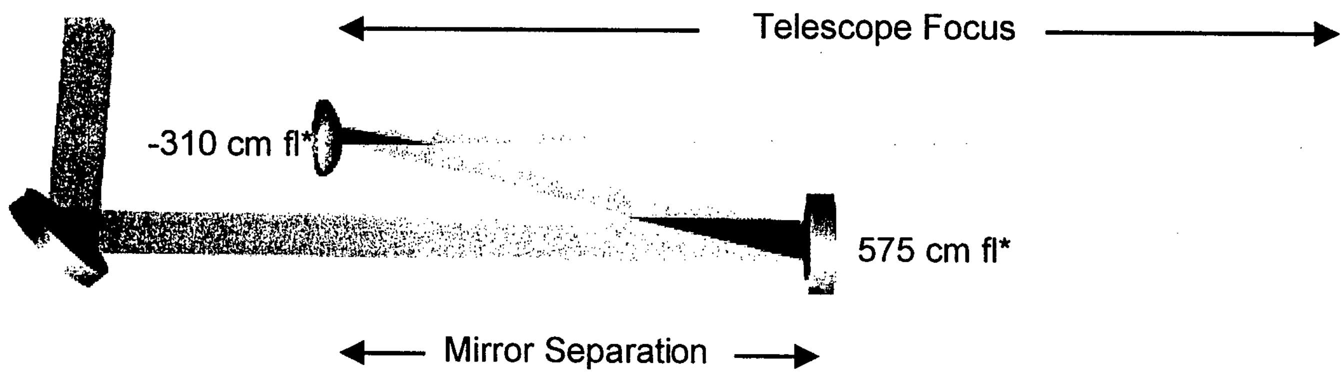
Phase II Accomplishments

- **Phase II – Initiated Jan 99**
  - A 5-Year Effort To Accomplish Vertical Launches to 30 km
  - With a 100 kW Laser. does this phrase go at the end of
  - Current Effort: Out Door Free Flight Tests To ~300 m.
    - Out door vertical free flights to ~40 m accomplished using
    - ablative fuel in near-field beam.
    - Lightcraft far-field beam performance measured with pendulum using
    - laboratory and FTT telescopes to ~533 m.
    - First, short (<1 m), vertical free flights conducted with
    - FTT telescope inside 500-meter building.
  - Continued Developments, Studies and Analyses
    - Characterize Model #200-3/4th with ceramic shroud.
    - Develop high temperature, lightweight ceramic optic with reflective
    - coating.
    - Continue flight dynamics and air inlet studies/design.
    - Obtain funding for 100 kW class CO2 electric discharge laser.

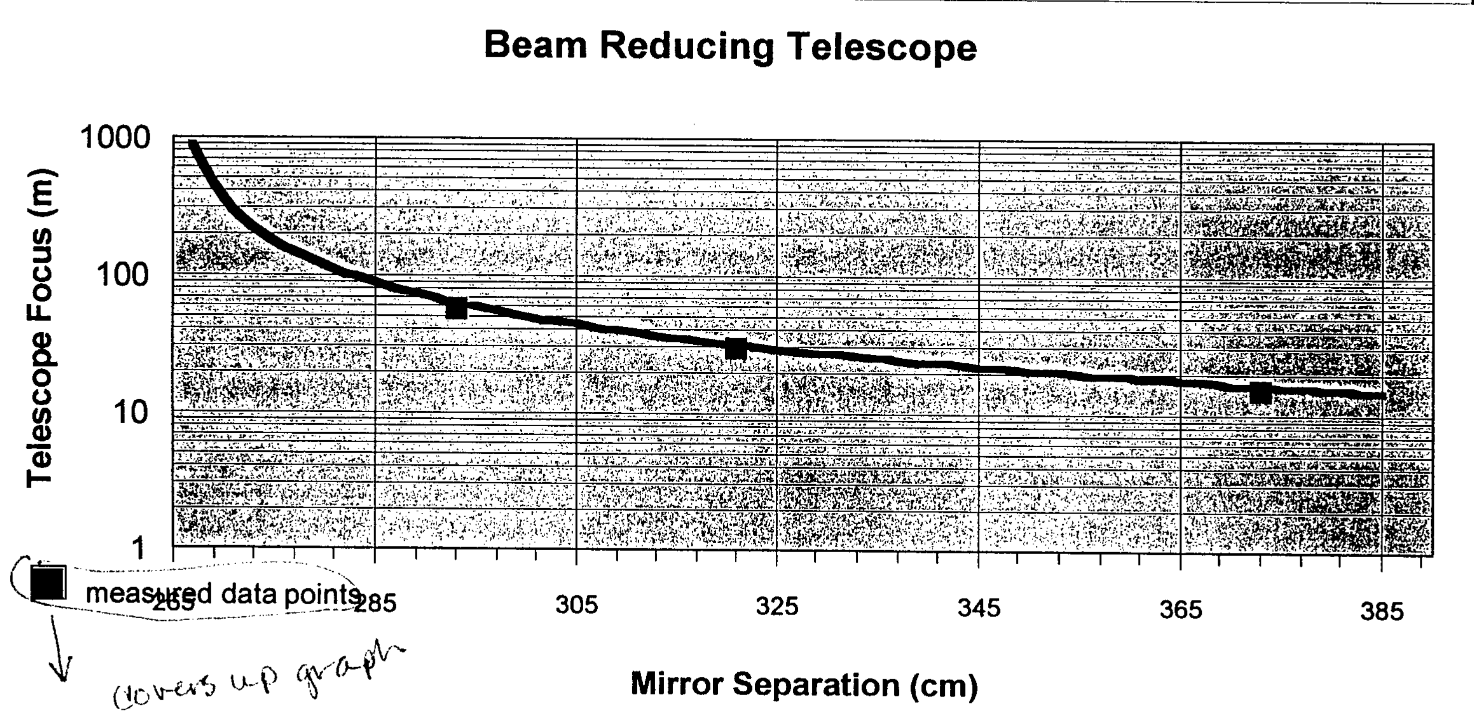
Pendulum Impulse Test Stand



Beam Reducing Telescope Used For Near Field Flights

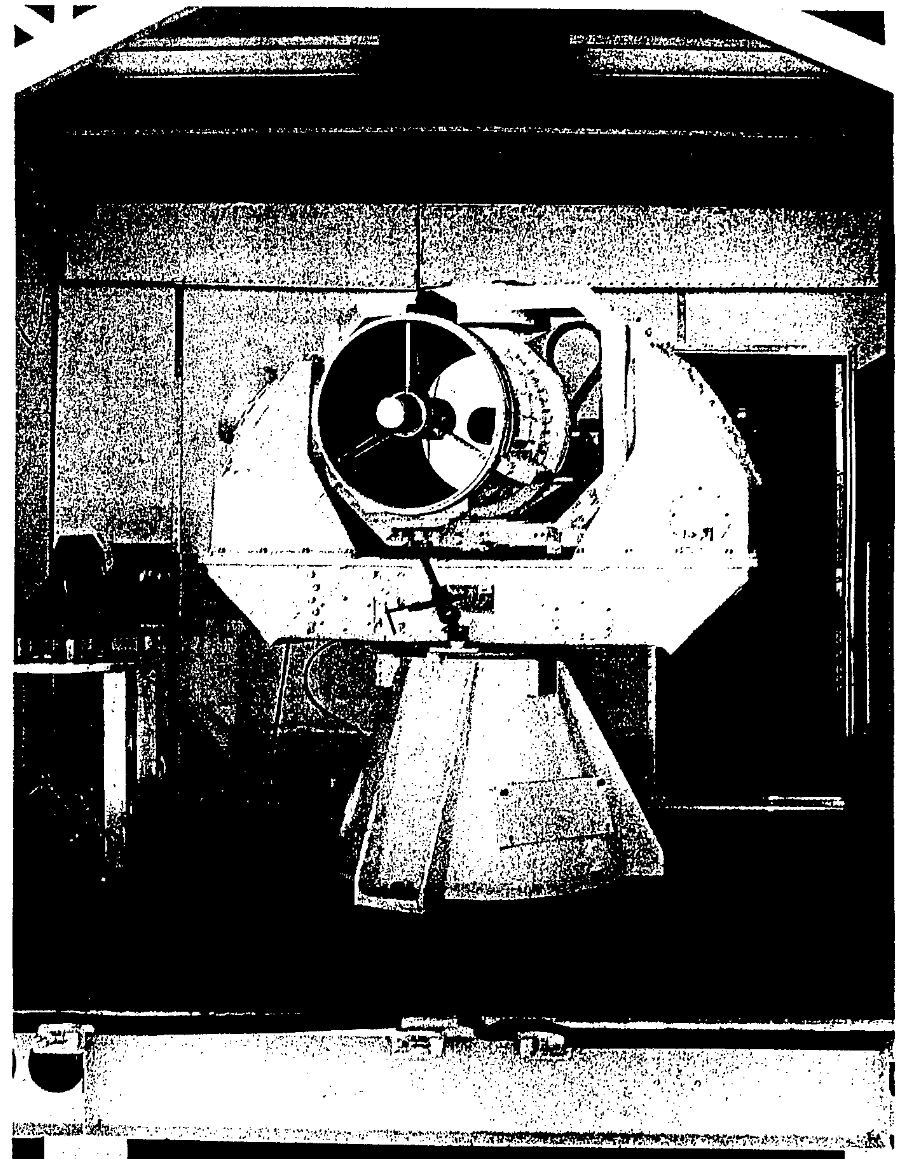


*focal lengths adjusted for curve fit

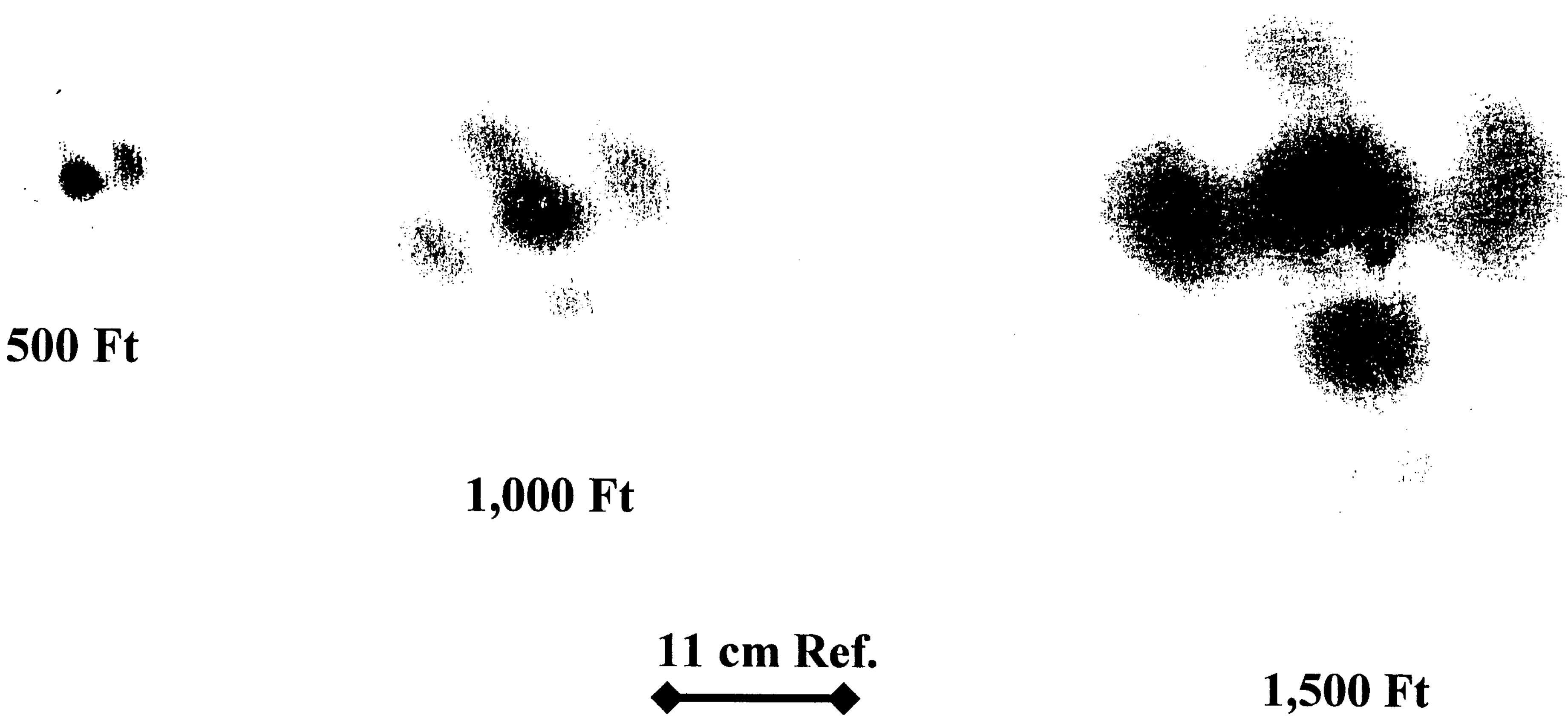


Field Test Telescope (FTT)

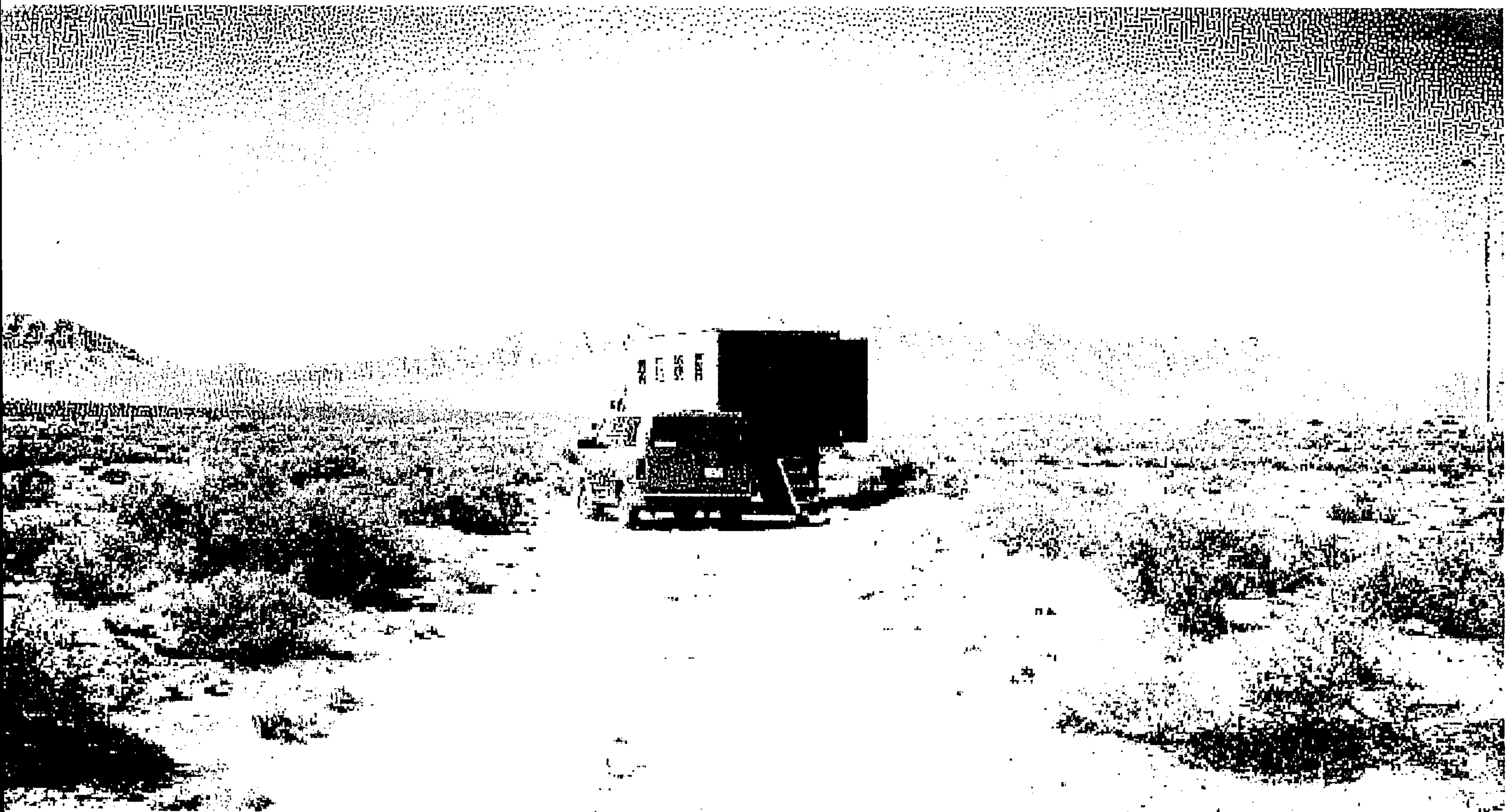
- A Laser Beam Handoff to This Telescope Should Allow Flights to Altitudes of ~300 m (1,000 ft).
  - 50 cm Diameter
  - Cassegrainian
  - Dynamic focusing



FTT Beam Burn Patterns

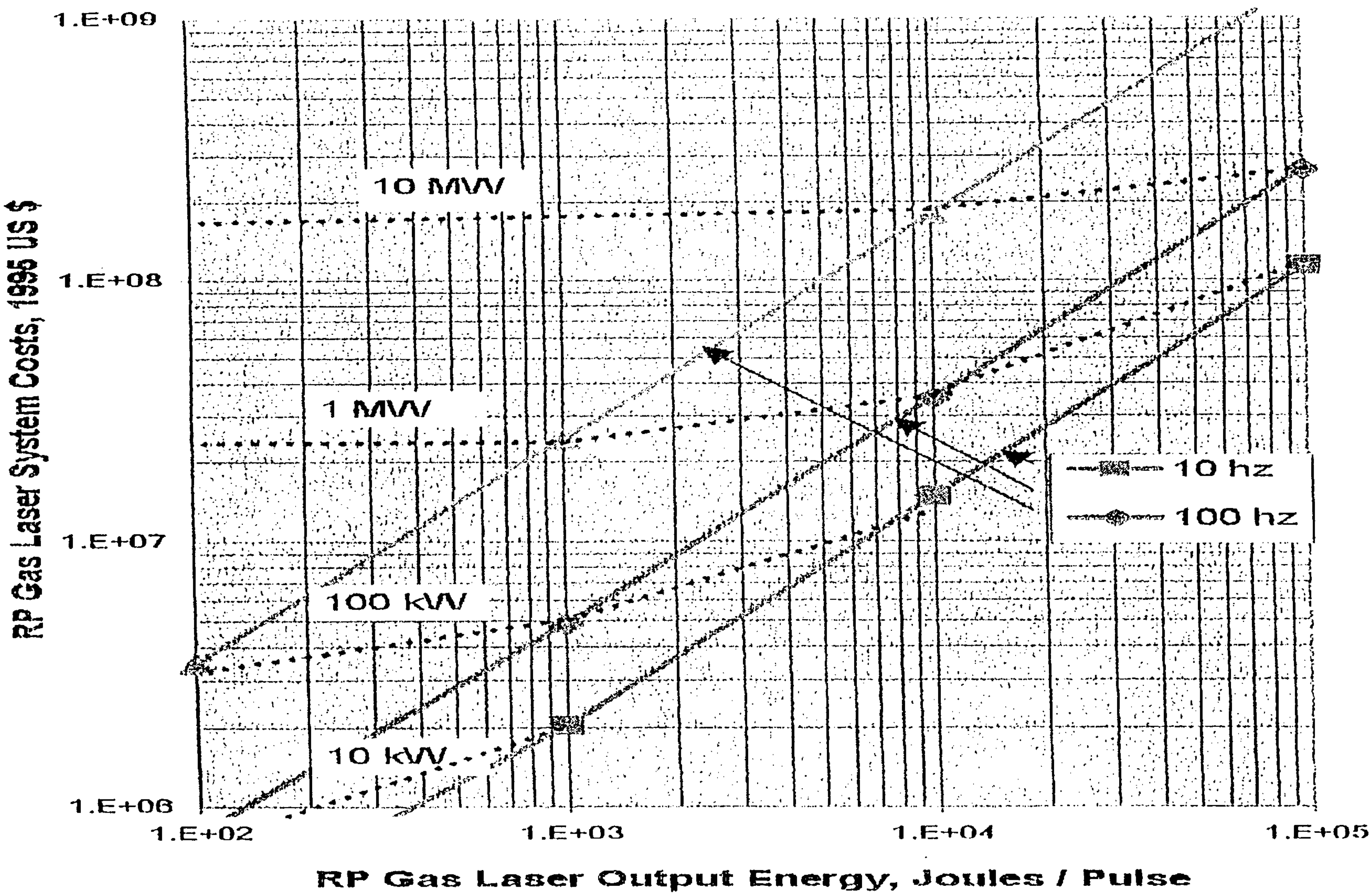


Optical Bench Set Up At 500-Ft Mark



RP GAS LASER COSTS ($\eta = 10\%$)

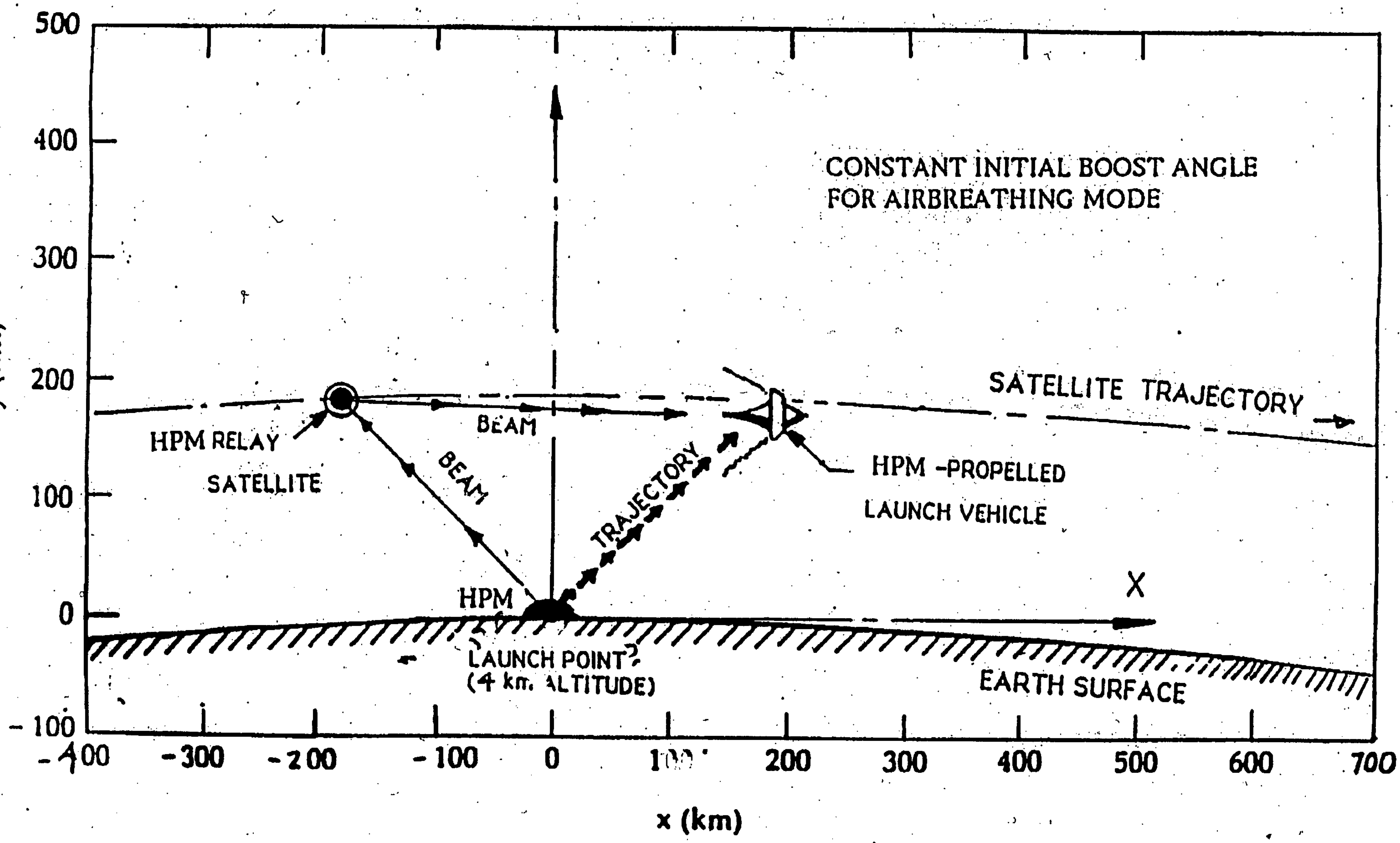
remove extra space



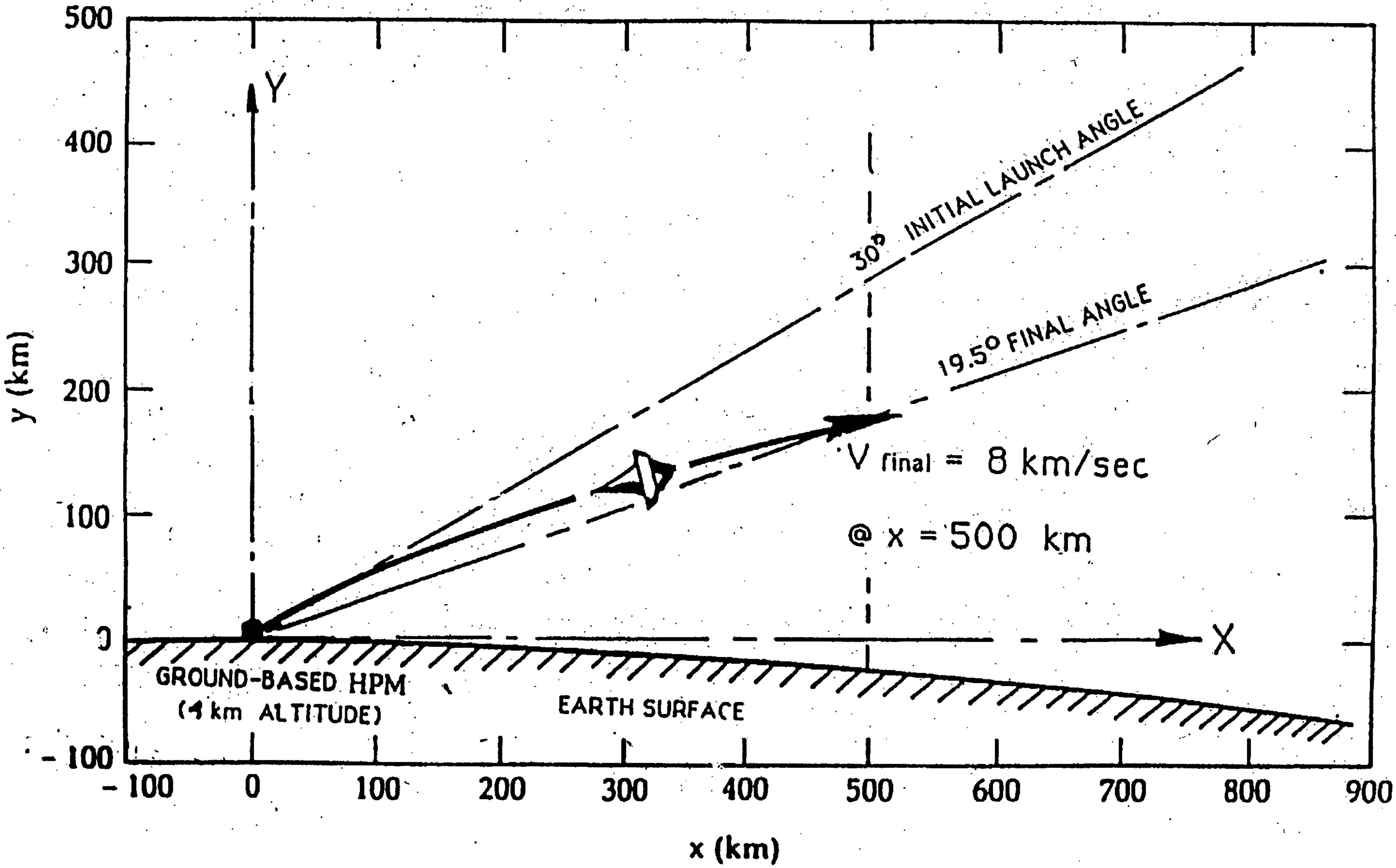
Introduction: Rules of Thumb for a Laser Launch System

- **Payload to LEO: 1 kg/MW (within a factor of 2)**
- **Time to orbit: 400 to 1000 seconds**
- **Laser range required: 400 to 1500 km**
  - Longer ranges require space-based laser or relay mirror
- **Electrical energy per kg to LEO:**
  150 - 300 kW-hr / laser efficiency
- **Max. launch rate**
  - To any orbit: 4 - 8 per hour, 100 - 200 per day
  - To one plane at 28.5°: ~ 8 - 32 per day
  - To one plane at 90°: ~ 2 - 8 per day

Launch With Relay Satellite



Direct Launch to Orbit (No Relay Satellite)

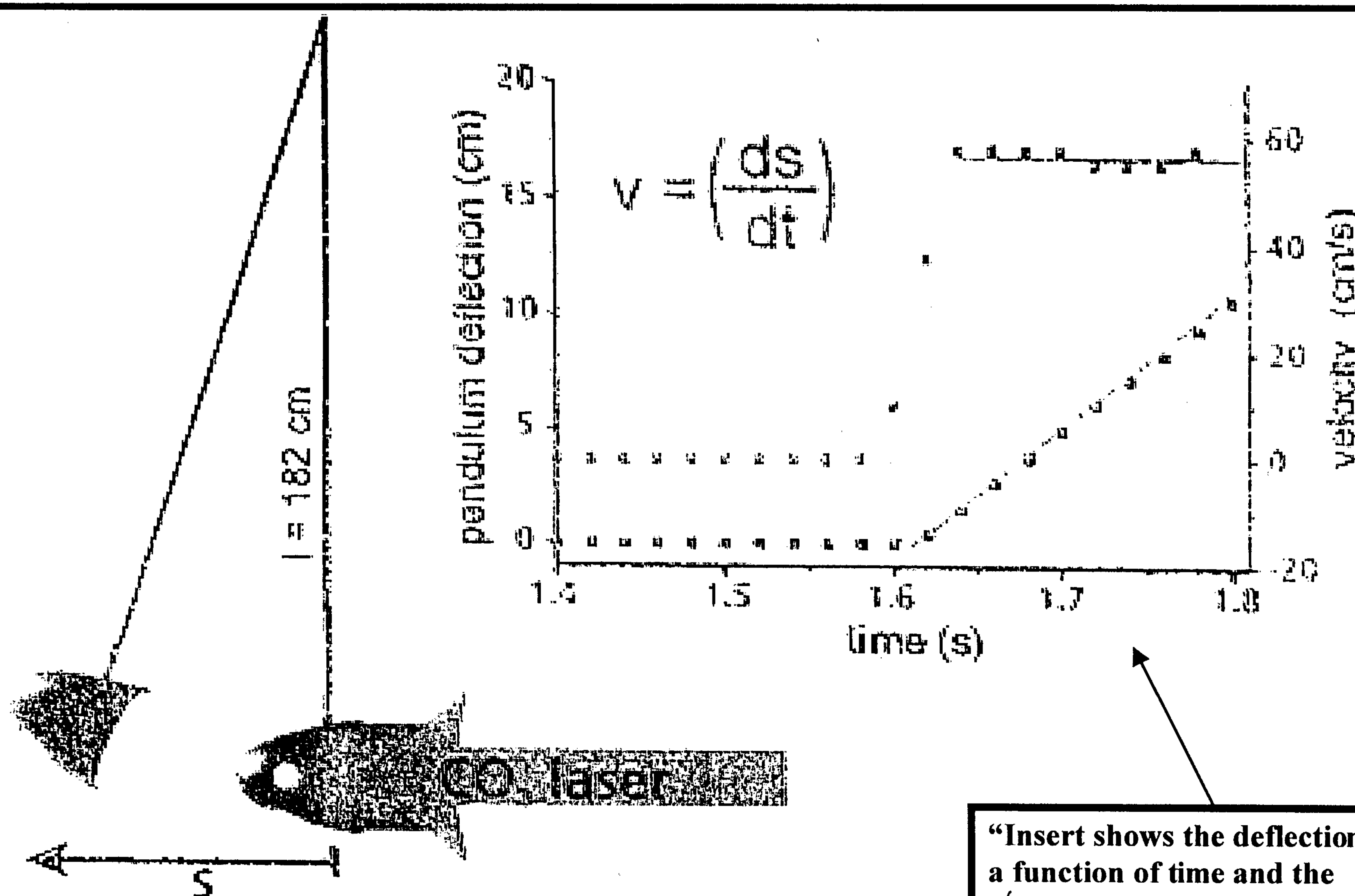


Laser Lightcraft Performance

A Paper By

Dr. Willy L. Bohn
DLR Institute of Technical Physics
D-70569 Stuttgart, Germany

Schematic Of Dr. Bohn's Pendulum Experiment*

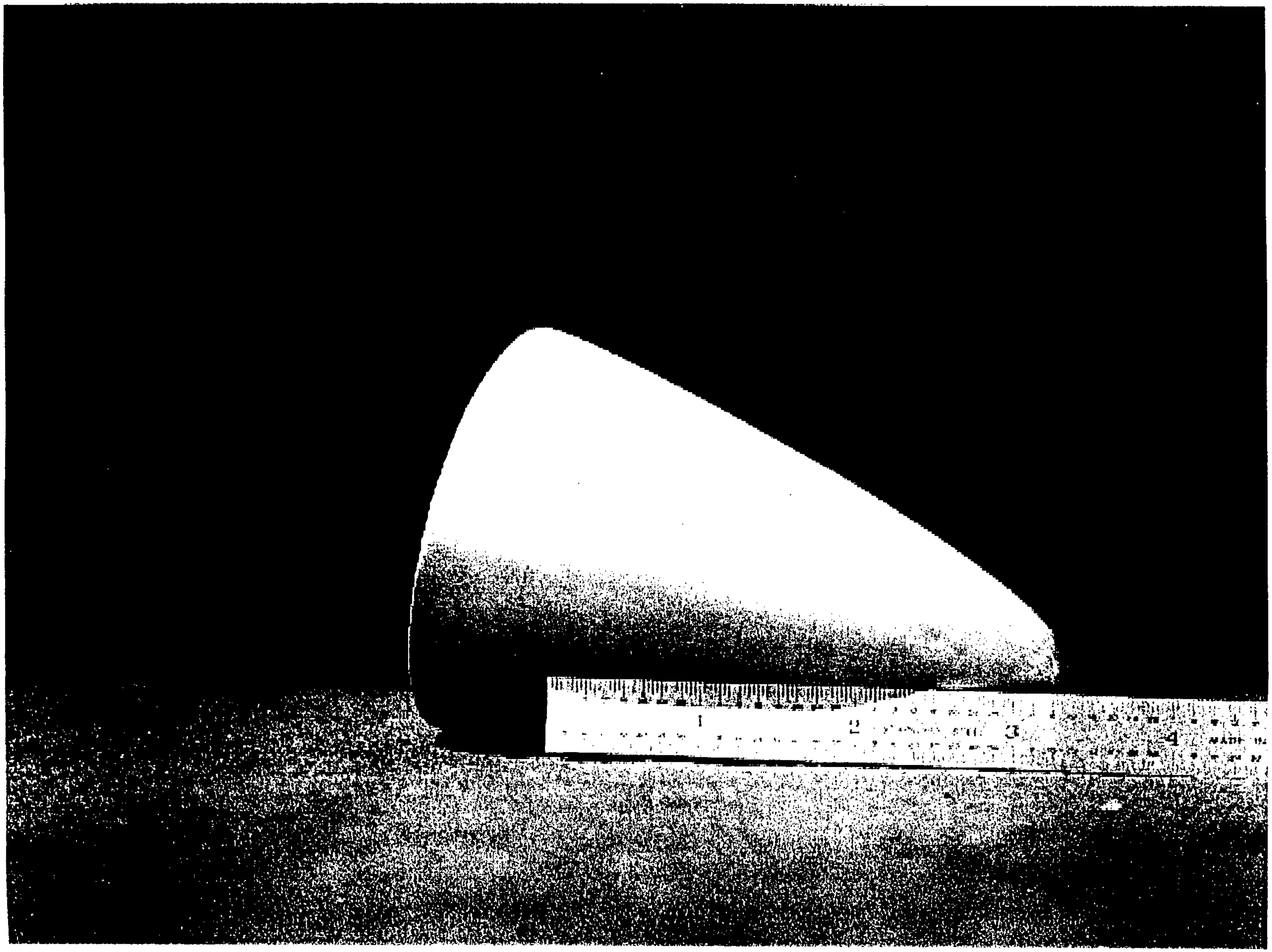


"Insert shows the deflection as a function of time and the corresponding lightcraft velocity"

* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics

AVCO Pulsejet Test Thruster

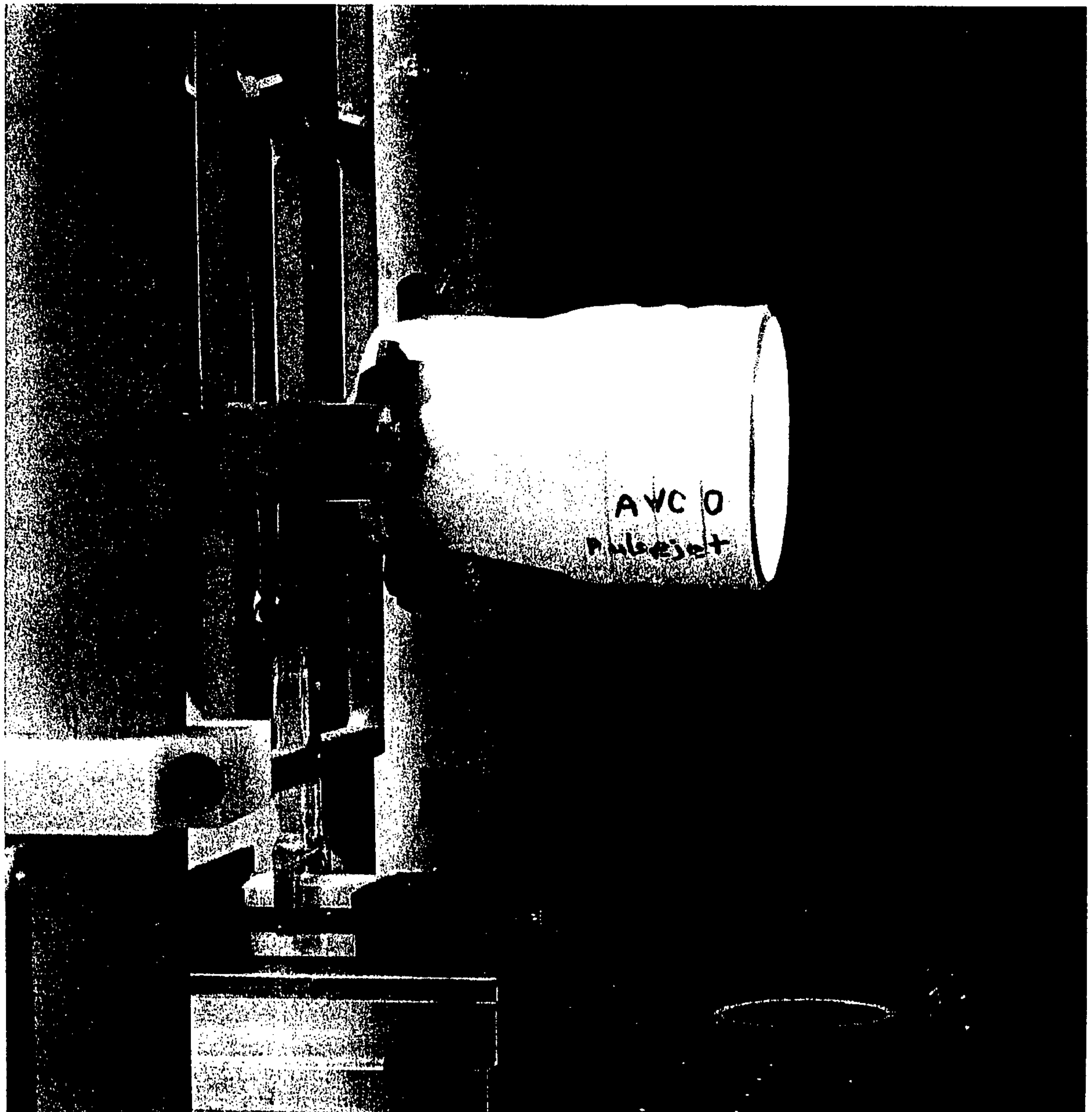
(White Sands Missile Range, July 99)



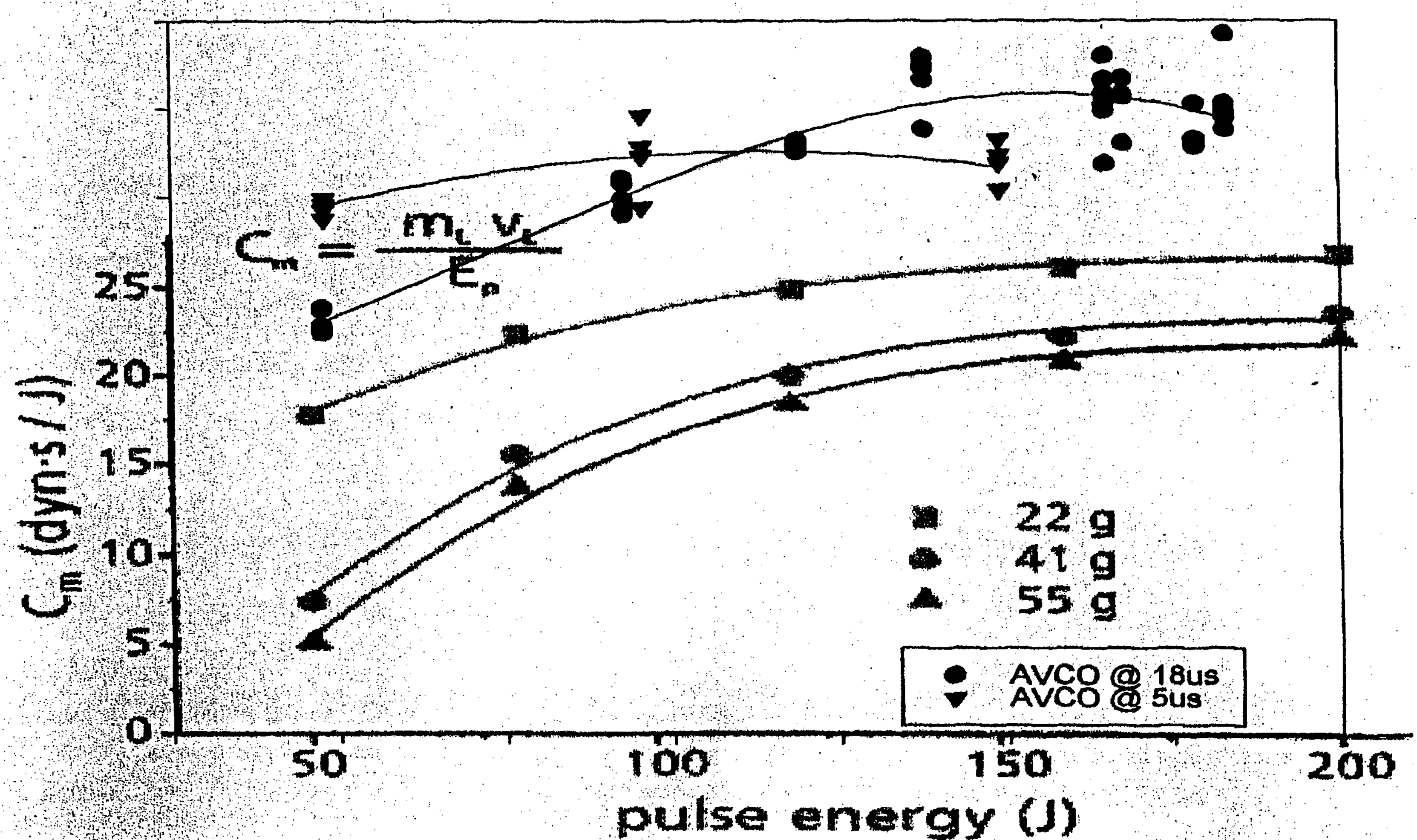
AVCO Pulsejet Test Thruster
(White Sands Missile Range, July 99)

Test of AVCO Pulsejet Thruster Mounted on Pendulum Impulse Test Stand

(White Sands Missile Range, July 99)

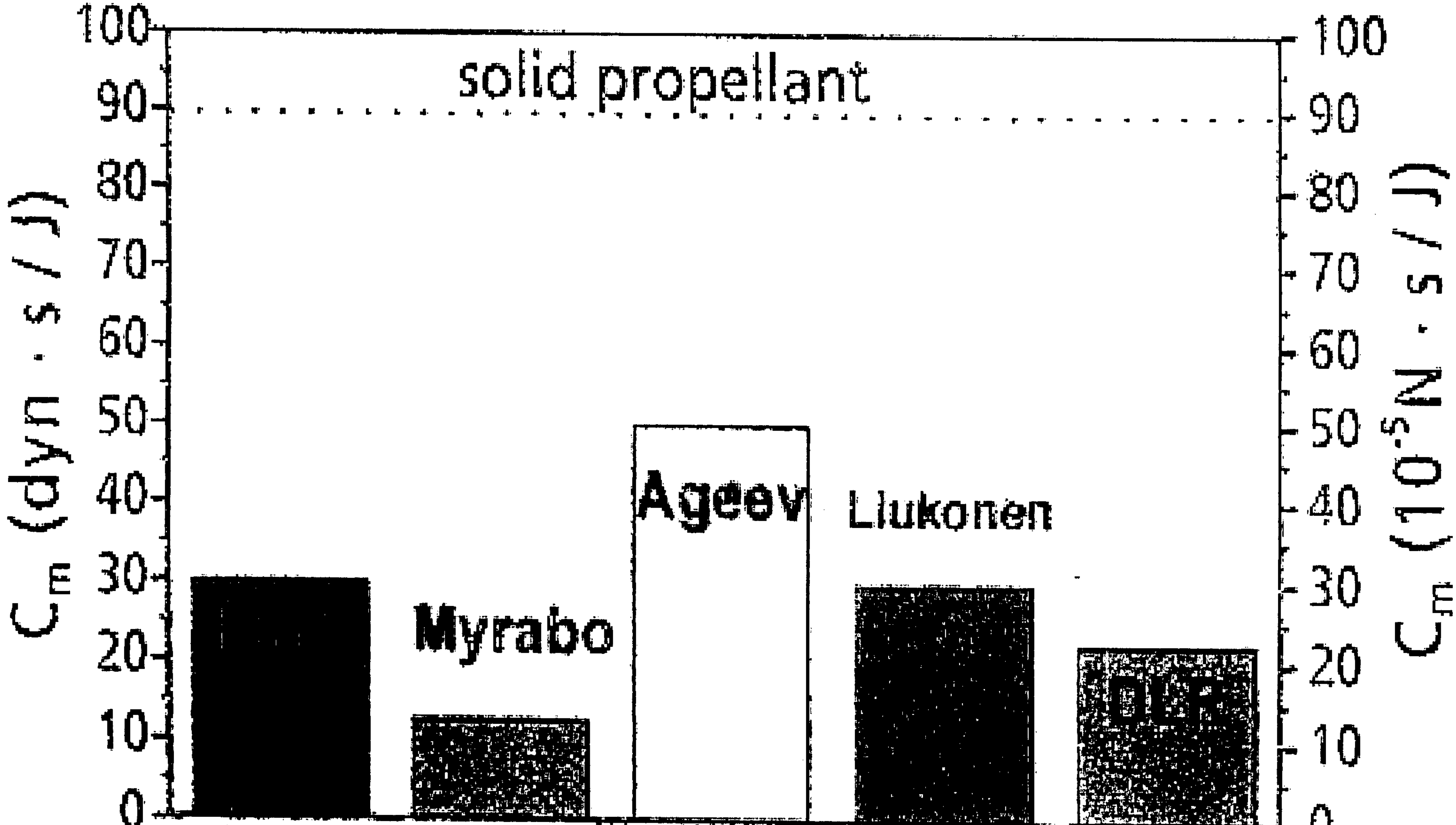


Comparison Of Dr. Bohn's Tests With AVCO Pulsejet Data Obtained At WSMR, July 99*



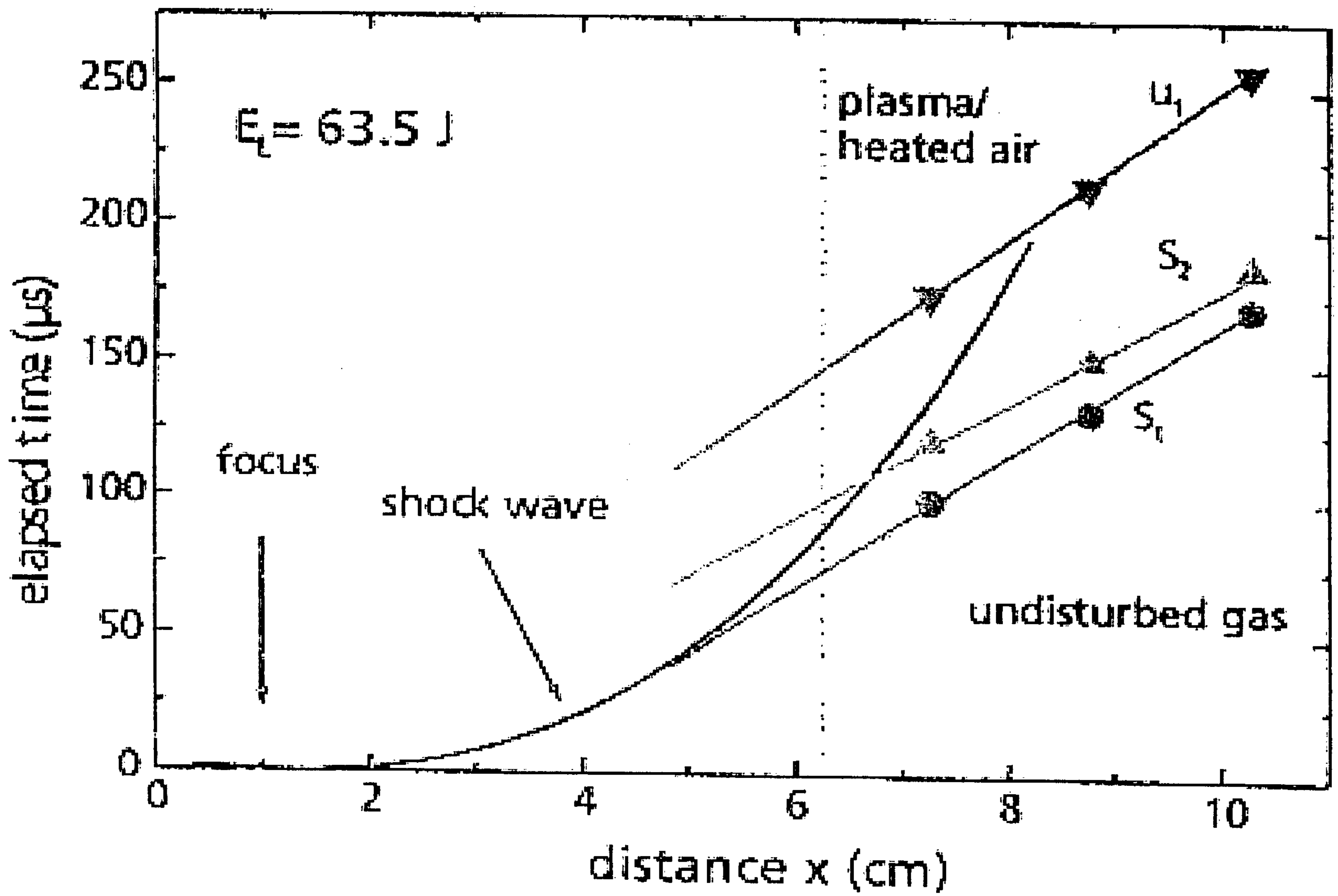
* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics

Comparison Of The Coupling Coefficient Obtained By Different Authors*



* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics

Evolution Of Shock Waves And Plasma In The Time-Space Domain*



* Taken from paper by Dr. Willy Bohn, DLR Institute of Technical Physics

Laser Propulsion Wrap-Up

- Many viable propulsion concepts possible using a laser source (mostly space propulsion)

- Laser propulsion system architecture cost dominated by laser source

- Promising near term concepts
  - Laser pulsejets (~~I.e.,~~ e.g., Lightcraft) and laser sail

*journal titles are italicized
*minimize use of abbreviat in references.

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*spell out names of places, centers, etc. which can be abbreviated (except laboratory)!
journal? If so, italicize

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*spell out 'Conference'

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